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Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment

Interagency Energy/Environment R&D Program Report

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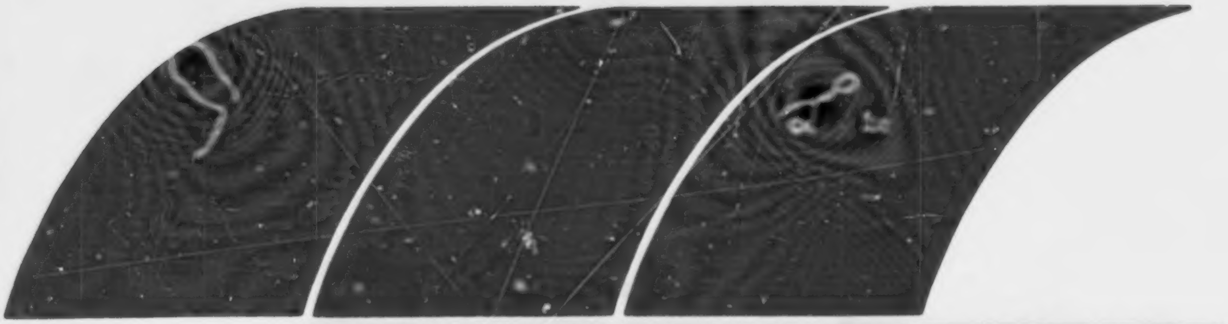

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Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment

by

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Washington, DC 20460

PREFACE

The Industrial Environmental Research Laboratory (IERL) of the U.S. Environmental Protection Agency (EPA) has the responsibility for insuring that pollution control technology is available for stationary sources to meet the requirements of the Clean Air Act, the Federal Water Pollution Control Act, and solid waste legislation. If control technology is unavailable, inadequate, or uneconomical, then financial support is provided for the development of the needed control techniques for industrial and extractive process industries. Approaches considered include: process modifications, feedstock modifications, add-on control devices, and complete process substitution. The scale of the control technology programs ranges from bench- to full-scale demonstration plants.

Monsanto Research Corporation (MRC) has contracted with the EPA to investigate the environmental impact of various industries which represent sources of pollution in accordance with the EPA's responsibility as outlined above. Dr. Robert C. Binning serves as MRC Program Manager in this overall program entitled "Source Assessment," which includes the investigation of sources in each of four categories: combustion, organic materials, inorganic materials, and open sources. Dr. Dale A. Denny of the Industrial Processes Division at Research Triangle Park serves as EPA Project Officer. Reports prepared in this program are of three types: Source Assessment Documents, State-of-the-Art Reports, and Special Project Reports.

Source Assessment Documents contain data on emissions from specific industries. Such data are gathered from literature, government agencies, and cooperating companies. Sampling and analysis are also performed by the contractor when the available information does not adequately characterize the source emissions. These documents contain information that is used by IERL to decide whether emissions reduction is necessary.

State-of-the-Art Reports include data on emissions from specific industries which are also gathered from the literature, government agencies and cooperating companies. However, no extensive sampling is conducted by the contractor for such industries. Results from such studies are published as State-of-the-Art Reports for potential utility by the government, industry, and others having specific needs and interests.

Special project reports provide specific information which is applicable to a number of source types or has special utility to EPA as part of a particular source assessment study. This special project report, "Preliminary Characterization of Emissions from Wood-Fired Residential Combustion Equipment," was prepared to provide a general characterization of air emissions from the residential combustion of wood. In this study, Dr. Ronald A. Venezia of the Chemical Processes Branch, Mr. Warren Peters of the Process Technology Branch, and Dr. John O. Milliken of the Special Studies Branch served as EPA Task Officers.

ABSTRACT

This report describes a study conducted to quantify criteria pollutants and characterize other atmospheric emissions from wood-fired residential combustion equipment. Flue gases were sampled from a zero clearance fireplace and two air-tight cast iron stoves (baffled and nonbaffled design). Four wood types were tested, oak-seasoned and green- and pine-seasoned and green. Samples were analyzed for particulates, condensable organics, nitrogen oxides, carbon monoxide, sulfur oxides, organic species, and individual elements.

Considerable variability was observed in results under different test conditions. Average emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, compared favorably with other studies on residential wood combustion. In most cases, variations in emission rates could not be correlated with either combustion equipment or wood type, and were ascribed to systematic errors or the effect of other variables such as excess air level or arrangement of wood. Combustion equipment did influence emissions of CO, NO_x and POM's. Emissions of CO and POM's were higher from wood-burning stoves, while NO_x emissions were higher from fireplaces. The only significant effect of wood type was the production of larger amounts of organic materials during the combustion of green pine.

Particulate emissions were determined to be organic in nature (50% to 80% carbon) and of resinous quality. Condensable organic emissions were greater in magnitude than the filterable particulate emissions.

The report was submitted in partial fullfillment of Contract No. 68-02-1874 by Monsanto Research Corporation under the sponsorship of the U.S. Environmental Protection Agency. The study described in this report covers the period January 1979 to October 1979.

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ABBREVIATIONS

acf -- actual cubic feet

acfh -- actual cubic feet per hour

cfm -- cubic feet per minute

dscf -- dry standard cubic feet

GC-MS -- gas chromatograph-mass spectrometer

ICAP -- inductively coupled argon plasma

KD -- Kuderna-Danish

Nm^3 -- volume in cubic meters at standard conditions (i.e., 20°C and 1 atm)

POM -- polycyclic organic matter

ppm -- parts per million

SASS -- Source Assessment Sampling System

SIM -- selected ion mode

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SECTION 1

INTRODUCTION

Residential combustion of wood for space heating has found renewed interest in this country due to the rising cost of oil and natural gas and the uncertainty of their availability in the future. The popularity of burning wood in open fireplaces for aesthetic reasons has also increased greatly in recent years. Current estimates indicate that as many as 1.5 million new fireplaces and wood burning stoves are being installed annually. Existing knowledge of the emissions from the woodburning equipment indicates that this trend poses a potential environmental problem. This potential problem has been already realized in communities, where a high concentration of wood-burning units has caused local ambient air quality problems.

Only a limited amount of emissions data exists on residential wood combustion; however, these data indicate a high variability in emissions and suggest the possibility of potential hazardous levels of certain pollutant species. Various organic species including POM (polycyclic organic material) compounds are probably the most environmentally significant pollutants from residential wood combustion; although previous emission measurements have done little to identify or quantify them.

Because of the rapid growth of wood-burning for primary home heating and aesthetic purposes, both regional and national EPA officials have become concerned over the potential environmental impact of large-scale residential combustion of wood. Large-scale residential combustion of wood could produce a dramatic adverse effect on local air quality, and the EPA is responsible for averting or minimizing such effects. The major problem confronting the EPA has been the absence of an adequate data base upon which to make policy decisions.

The objective of this special project was to determine the physical and chemical characteristics of airborne emissions from wood-fired residential combustion equipment. These characterization data are necessary to supplement existing data on wood combustion so that more objective estimates of the impact of this source on ambient air quality can be made. The sampling program included the collection of sufficient field data to identify and quantify pollutants not previously measured and to supplement the data on known pollutants.

One fireplace and two woodburning stoves were tested while burning four types of wood. Exit gases were measured for particulates, condensable organics, sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), organic species including polycyclic organic materials (POM's), and individual elements. Bioassay tests were also conducted on the stack emissions and bottom ash. Testing was performed at Auburn University, Auburn, Alabama, during March and April 1979, and samples were analyzed later in the year.

SECTION 2

SUMMARY

This report presents the results of a test program conducted by the U.S. Environmental Protection Agency, Monsanto Research Corporation, and Auburn University to characterize emissions from wood-fired residential combustion equipment. The program was undertaken because of the increased usage of wood for home heating and aesthetic purposes and because of the potential environmental impact from increased emission levels. Although a limited amount of testing has been done by others on this source type, those tests have not thoroughly characterized emissions of organic species, which have the greatest potential for adverse effects.

In this program emission testing was conducted on a zero-clearance fireplace and two air-tight cast iron stoves. The air-tight stoves were of common design; one was baffled to increase flue gas retention. The units were larger varieties capable of accepting about 15 kg of wood per charge. Combustion conditions were maintained in the air-tight stoves by manipulation of the air inlet vents until combustion was not excessive (flames reaching into the exhaust pipe) but also not starved for air (no visible flame present). Stack temperature was also used to aid in this control. The wood burning rate ranged from 6.0 kg/hr to 8.4 kg/hr. The fireplace was operated with glass doors open and damper fully open. The wood burning rate in the fireplace ranged from 9.6 kg/hr to 11 kg/hr.

Thermal efficiencies for air-tight stoves have been reported to be as high as 80%; however, in this program the two units tested were operated in the range of 40% to 60% thermal efficiency (useful heat recovered, divided by the heat content of the wood). The fireplace employed was tested and found to have a maximum thermal efficiency of about 23%. This study was conducted under conditions which approximated optimum thermal efficiency for the fireplace. Tests were conducted on each unit burning four varieties of wood. Both yellow pine and red oak were obtained (green and seasoned) locally in Auburn, Alabama, where testing was conducted.

Quantitative emissions testing employed EPA methods from the Federal Register to measure sulfur oxides (SO_x), nitrogen oxides

oxides (NO_x), and carbon monoxide (CO). EPA Method 5 was used to measure both filterable particulate matter and condensable organics. Semiquantitative testing was performed using modified EPA methods and a Source Assessment Sampling System (SASS train) to measure POM's, organic species, and trace elements. Volatile hydrocarbons were measured by GC/FID, and aldehydes were collected by midget impingers containing sodium bisulfite and analyzed by GC. Samples for bioassay were collected with the SASS train. A technique to screen for POM compounds was also tested in this program.

Average emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, for the three combustion devices and four test woods, as measured in this program, are presented in Table 1 for criteria pollutants and total POM's. Results indicate that the air-tight stoves have significantly higher emission rates for CO and POM's, while NO_x emissions were greater from the fireplace. Wood type did not appear to be a major variable, although combustion of green pine produced higher levels of organic pollutants. There are many significant variables in the residential wood combustion process, and the results of this program only represent one set of conditions. However, they do represent a significant portion of the source population. Indications are that wood-burning rate is a variable worthy of future study. Other conclusions and observations were made during this test program. Filterable particulate emissions were determined to be organic in nature (50% to 80% carbon) and had resinous qualities. Condensable organic emissions were greater in magnitude than the filterable particulates, often by a factor of two. These two emission species are sometimes reported collectively as total particulate emissions. Sulfur oxide emissions were found to be quite low (approximately 0.2 g/kg) because of the low fuel sulfur content.

Elemental emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, as determined from one SASS train run, were generally on the order of 1 mg/kg or less. These values are two or three orders of magnitude lower than typical elemental concentrations in wood, indication that most of the wood elemental content is not released to the atmosphere upon combustion.

Flue gas temperature measurements indicated that the combustion process was cyclic in nature and that certain emissions may be affected by this. Carbon monoxide emissions were found to vary by more than an order of magnitude during burning of one charge of wood. Nitrogen oxides, on the other hand, were fairly stable and unaffected by changing combustion conditions. It is expected that organic emissions, or those directly related to organic emissions (such as particulates), will follow a pattern similar to that of the CO emissions; however, this was not quantified in this program.

TABLE 1. SUMMARY OF EMISSION RESULTS FOR CRITERIA POLLUTANTS AND POM's FROM WOOD-FIRED RESIDENTIAL COMBUSTION EQUIPMENT

Wood burning device	Wood type	Emission rate, g/kg[a] (μg/J)[b]						
		Particulate matter	Condensable organics	Volatile hydrocarbons	NO_x	SO_x	CO	POM
Fireplace	Seasoned oak	2.3 (0.13)	6.3 (0.35)	19 (1.1)	2.4 (0.13)		30 (1.7)	0.025 (0.0014)
Fireplace	Green oak	2.5 (0.19)	5.4 (0.40)		1.9 (0.14)		22 (1.6)	
Fireplace	Seasoned pine	1.8 (0.10)	5.9 (0.32)		1.4 (0.08)		21 (1.2)	
Fireplace	Green pine	2.9 (0.21)	9.1 (0.67)		1.7 (0.13)		15 (1.1)	0.036 (0.0026)
Baffled stove	Seasoned oak	3.0 (0.17)	4.0 (0.22)		0.4 (0.02)		110 (6.2)	0.21 (0.012)
Baffled stove	Green oak	2.5 (0.19)	3.8 (0.28)		0.7 (0.05)		120 (9.0)	
Baffled stove	Seasoned pine	3.9 (0.21)	4.1 (0.23)	2.8 (0.15)	0.5 (0.03)		270 (15)	0.37 (0.020)
Baffled stove	Green pine	7.0 (0.51)	12 (0.88)		0.8 (0.06)		220 (16)	
Nonbaffled stove	Seasoned oak	2.5 (0.14)	6.0 (0.34)		0.4 (0.02)	0.16 (0.009)	370 (21)	0.19 (0.011)
Nonbaffled stove	Green oak	1.8 (0.13)	3.3 (0.25)	0.3 (0.02)	0.5 (0.04)		91 (6.8)	
Nonbaffled stove	Seasoned pine	2.0 (0.11)	5.6 (0.31)		0.2 (0.01)	0.24 (0.013)	150 (8.2)	
Nonbaffled stove	Green pine	6.3 (0.46)	10 (0.74)	3.0 (0.22)	0.4 (0.03)		97 (7.1)	0.32 (0.024)

[a] Grams of pollutant emitted per kg of wood (as-received basis) burned.

[b] Blanks indicate no data were obtained.

In most cases over 50% of the organic material collected during sampling was nonchromatographable by GC/MS. This nonchromatographable material was indicated to be largely high molecular weight organic acids and high molecular weight fused ring aromatics (e.g., POM's). Over 75 organic compounds were identified upon characterization of the chromatographable organic material present in the flue gas; 22 of these were POM's, while the remaining organic materials identified were dominated by aldehydes, furans, phenols, and naphthalenes.

The POM screening test conducted in the field was found to compare fairly well with more quantitative measurements. Because the field technique is rapid and somewhat subjective, results are determined as a range of POM concentrations. These ranges varied from encompassing the quantitative value to differing by a factor of 15 from the more quantitative results.

Twelve SASS runs were made to provide samples for bioassay: one for each test condition. Each SASS run resulted in two samples for bioassay: The first consisted of the methylene chloride extract of all front-half material (cyclone and filter catches and wash residues). The second sample submitted consisted of the methylene chloride extract of the XAD-2 resin and the methylene chloride rinse of the XAD-2 module. Twelve samples of each were submitted for Salmonella/microsome mutagenesis assay (Ames Test) and clonal toxicity (CHO) assay. Combustion residue samples (ash) were also collected from each test condition, and eight out of twelve were submitted for bioassay. All of the SASS train samples showed mutagenic activity (with the Ames test) and also exhibited high to moderate toxicity by the CHO assay. Ash samples showed no mutagenic response and exhibited either no toxicity or low toxicity.

Because the significant pollutants from wood-burning are related to inefficient combustion, their emission levels may be sensitive to variables in mode of operation such as fuel charge, physical arrangment of fuel and air-to-fuel ratio. Further studies on residential wood burning would be useful to quantify the effects of these variables and other design variables. Design modifications and standards for operation should be studied as a means of improving combustion and reducing emissions.

SECTION 3

TEST PROGRAM AND PROCEDURES

DESIGN OF TEST PROGRAM

The objectives of this program were to 1) identify emissions from residential wood-fired combustion equipment not previously characterized, 2) measure emission rates of all major emissions from these wood-fired units, and 3) conduct bioassay analyses on the emissions. Table 2 presents a summary of the test program, including the major test variable and the types of samples that were collected and analyzed.

Prior to this study five other testing programs had been completed to measure emissions from residential wood-fired combustion (1-5). Most of those programs concentrated on emissions of particulate matter; although some data were obtained on carbon monoxide (CO) and hydrocarbon emissions. In one program, three measurements of POM compounds were made; in another program, the presence of carbonyls, phenols, organic acids, and nitrogen oxides (NO_x) was established. Only two of these studies employed

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TABLE 2. SUMMARY OF OVERALL TEST PROGRAM

Test Condition	Combustion equipment			Wood				Samples collected and analyzed						
		Airtight stove		Type		Moisture level		EPA Method 5				SASS[b] train samples for chemical assay	Volatile[c] hydrocarbon	Aldehydes[d]
	Fireplace	No. 1	No. 2	Oak	Pine	Low (seasoned)	High (green)	Front-half particulates	Condensable organics	POM[a]	High molecular-weight organic speciation[a]			
A-1	x			x		x		x		x	x			
A-1	x			x		x		x	x			x	x	x
A-2	x			x			x	x						
A-2	x			x			x	x	x					
A-3	x				x	x		x						
A-3	x				x	x		x	x					
A-4	x				x		x	x		x	x			
A-4	x				x		x	x	x					
B-1		x		x		x		x		x	x			
B-1		x		x		x		x	x					
B-2		x		x			x	x	x					
B-2		x		x			x	x	x					
B-3		x			x	x		x		x	x			
B-3		x			x	x		x	x				x	x
B-4		x			x		x	x	x					
B-4		x			x		x	x	x					
C-1			x	x		x		x		x	x			
C-1			x	x		x		x	x					
C-2			x	x			x	x						
C-2			x	x			x	x	x				x	x
C-3			x		x	x		x						
C-3			x		x	x		x	x					
C-4			x		x		x	x		x	x			
C-4			x		x		x	x	x			x	x	x

(continued)

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[a] POM train employing EPA Method 5 equipment supplemented with XAD-2 resin trap.

[b] Particulates by size (<1 μm, 1 μm to 3 μm, 3 μm to 10 μm, >10 μm), organic species, POM, trace elements.

[c] GC/FID.

[d] Midget impinger train; formaldehyde by Schiff's test colorimetric method; other aldehydes by GC/FID.

TABLE 2 (continued)

Test condition	Combustion equipment			Wood				Samples collected and analyzed							
		Airtight stove		Type		Moisture level									
	Fireplace	No. 1	No. 2	Oak	Pine	Low (seasoned)	High (green)	NO_x[e]	CO[f]	O_2, CO_2[g]	C, H, and N of particulate[h]	SASS train samples[i] for bioassay	POM screening[j]	Ash samples for bioassay	SO_2
A-1	x			x		x		x	x	x		x	x		
A-1	x			x		x		x	x	x				x	
A-2	x			x			x	x	x	x		x	x		
A-2	x			x			x	x	x	x				x	
A-3	x				x	x		x	x	x		x	x		
A-3	x				x	x		x	x	x				x	
A-4	x				x		x	x	x	x	x	x	x		
A-4	x				x		x	x	x	x	x			x	
B-1		x		x		x		x	x	x		x	x		
B-1		x		x		x		x	x	x				x	
B-2		x		x			x	x	x	x		x	x		
B-2		x		x			x	x	x	x				x	
B-3		x			x	x		x	x	x	x	x	x		
B-3		x			x	x		x	x	x	x			x	
B-4		x			x		x	x	x	x		x	x		
B-4		x			x		x	x	x	x				x	
C-1			x	x		x		x	x	x	x	x	x		
C-1			x	x		x		x	x	x	x			x	x
C-2			x	x			x	x	x	x		x	x		
C-2			x	x			x	x	x	x				x	
C-3			x		x	x		x	x	x		x	x		
C-3			x		x	x		x	x	x				x	x
C-4			x		x		x	x	x	x		x	x		
C-4			x		x		x	x	x	x				x	

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[e] EPA Method 7.

[f] Orsat for CO at >1,000 ppm; Drager tube for CO at <1,000 ppm.

[g] Orsat.

[h] Perkin Elmer elemental analyzer.

[i] Particulates by size (<1 μm, 1 μm to 3 μm, 3 μm to 10 μm, >10 μm). Samples collected for bioassay testing of emission species by EPA.

[j] POM screening performed on two types of samples: POM samples collected via the use of the POM train and POM samples collected via a midget impinger train containing methylene chloride.

standard sampling and analytical methods approved by the EPA. Results of these studies indicated that emissions from the residential combustion of wood are highly variable and additional data are necessary to adequately perform an environmental impact assessment. The available data on POM emissions, although limited, indicate that this pollutant may be emitted at a rate significantly higher (on a per Joule basis) than from residential oil or gas combustion.

Two air-tight wood burning stoves and one zero-clearance fireplace were selected for testing in this program. Although many varieties of residential wood-burning equipment exist, the designs chosen for testing represent a significant portion of the equipment population. Because wood is such a highly variable fuel, an in-depth assessment of representative fuel woods and the resulting combustion emissions was beyond the scope of this program. The wood types chosen for testing - red oak (green and seasoned) and yellow pine (green and seasoned) - although not available in all regions of the country, are representative of the range of wood types burned in this source category.

Table 3 presents the test matrix code employed in this program. The code uses a letter to designate the combustion equipment tested and a number to designate the wood type. This code had its greatest utility in identifying and tracking test runs, field samples, data sheets, sample logs, analysis requests and analytical results.

TABLE 3. TEST MATRIX CODE EMPLOYED FOR SAMPLE CONTROL

Combustion equipment	Wood type Seasoned oak	Green oak	Seasoned pine	Green pine
Fireplace	A-1	A-2	A-3	A-4
Baffled stove	B-1	B-2	B-3	B-4
Nonbaffled stove	C-1	C-2	C-3	C-4

Test Site and Facilities

Investigations into the emissions from wood-burning stoves and fireplaces were conducted at the wood-burning laboratory of Auburn University. This test site is operated by the Department of Mechanical Engineering at Auburn with funds supplied by the Department of Energy, the Fireplace Institute, and private manufacturers.

This facility has over 15 different wood combustion devices available for testing. Thermal efficiency testing can be performed either by the flue gas analysis technique or by calorimeter room.

The calorimeter room was not available for this study. Two electronic balances were, however, available which can support combustion equipment for wood burning rate determination. A computer terminal was installed at the test site to be used for data logging, storage and manipulation, and thermal efficiency determination. Typical computer outputs are shown in Appendix A.

Emission testing was facilitated by the large work area available and support facilities such as tables, scaffolding, ample electrical circuits, power tools, hardware, chilled running water for impinger trains, lab benches, a refrigerator for sample preservation, and sinks.

The staff at Auburn provided technical assistance in setting up and carrying out this program, provided combustion units and supporting material, and conducted thermal efficiency tests parallel to emission testing.

Combustion Equipment

The testing program was designed to measure the emissions from typical wood-fired combustion equipment burning wood types representative of the varieties available in the United States. The selection of combustion equipment was determined by the representativeness of the equipment based on current trends. According to the U.S. Bureau of the Census, 452,000 new homes were built in 1975 with fireplaces, and about 550,000 wood-burning stoves were shipped by manufacturers (6, 7). A large variety of stoves encompassing several basic combustion-chamber designs are available on the market. Because the emphasis is now on energy efficiency, air-tight metal stoves, which are claimed to be 50% to 70% energy efficient, are becoming very popular. As the figures indicate, fireplaces remain popular either for aesthetic reasons or out of ignorance of their inefficient heat recovery.

The fireplace chosen for study was a sheet metal zero-clearance type equipped with glass doors and a forced-air circulation system to distribute heat away from the firebox. All tests on the fireplace were performed with the glass doors open and forced air fans on. The firebox was lined with 0.025 m firebrick and the flue damper was nonpositioning, i.e., it was either wide open or fully closed. The fuel bed was supported by a cast iron grate elevating the fire about 0.1 m from the bottom of the firebox. Flue gases from the fireplace exited from the top of the firebox

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(6) Construction Report; Bureau of the Census Series C26; Characteristics of New Housing: 1976. U.S. Department of Commerce, Washington, D.C., July 1977. 77 pp.

(7) Current Industrial Reports, Selected Heating Equipment. Bureau of the Census MA-34N(75)-1, U.S. Department of Commerce, Washington, D.C., July 1976. 6 pp.

through an 0.2 m (8-in.) metal duct. This duct was made from the inner wall of a triple-wall stove pipe which had the middle and outer wall removed to facilitate sampling. The flue pipe discharged into a roof vent approximately 4 meters above the top of the firebox. This method of discharge reduced the effect of wind on the combustion air draft. Figure 1 shows the location of the various sampling points relative to the top of the firebox. These points were essentially the same for sampling of the wood-burning stoves.

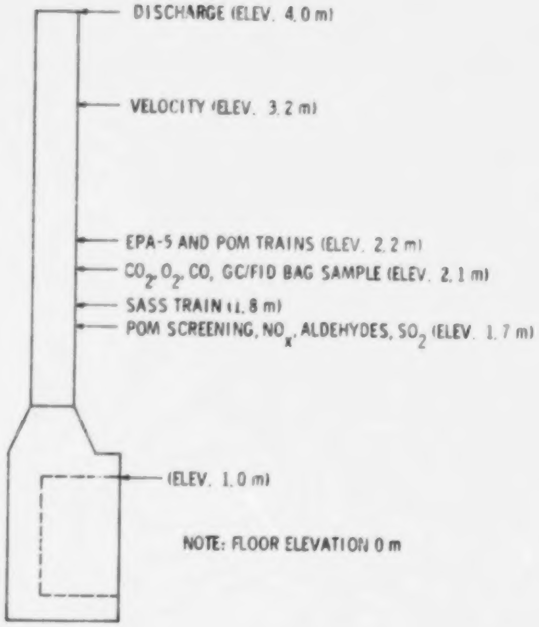
DISCHARGE (ELEV. 4.0 m)
VELOCITY (ELEV. 3.2 m)
EPA-5 AND POM TRAINS (ELEV. 2.2 m)
CO_2, O_2, CO, GC/FID BAG SAMPLE (ELEV. 2.1 m)
SASS TRAIN (1.8 m)
POM SCREENING, NO_x, ALDEHYDES, SO_2 (ELEV. 1.7 m)
(ELEV. 1.0 m)
NOTE: FLOOR ELEVATION 0 m

Figure 1. Sampling point elevations for testing of fireplace and wood stoves.

The two wood burning stoves tested were of the popular air-tight variety. One was baffled and the other was nonbaffled. Both were cast iron combustion units with a flat upper surface available for cooking but not often employed for that purpose. Combustion air is provided in these units by a passive draft system in which room air enters the firebox through adjustable vents in the door located at the front of the unit.

The baffled stove, shown in Figure 2 (8), was an air tight, two-level, boilerplate radiant heater. The firebox, which is made of steel plate, was 0.69 m long, 0.46 m high, and 0.44 m wide, and

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(8) Dyer, D. F., T. T. Maxwell, and G. Maples. Improving the Efficiency, Safety and Utility of Woodburning Units, Volume 3, Quarterly Report No. W.B.-4. Contract ERDA EC77S05552, Department of Energy, Washington, D.C., September 15, 1978.

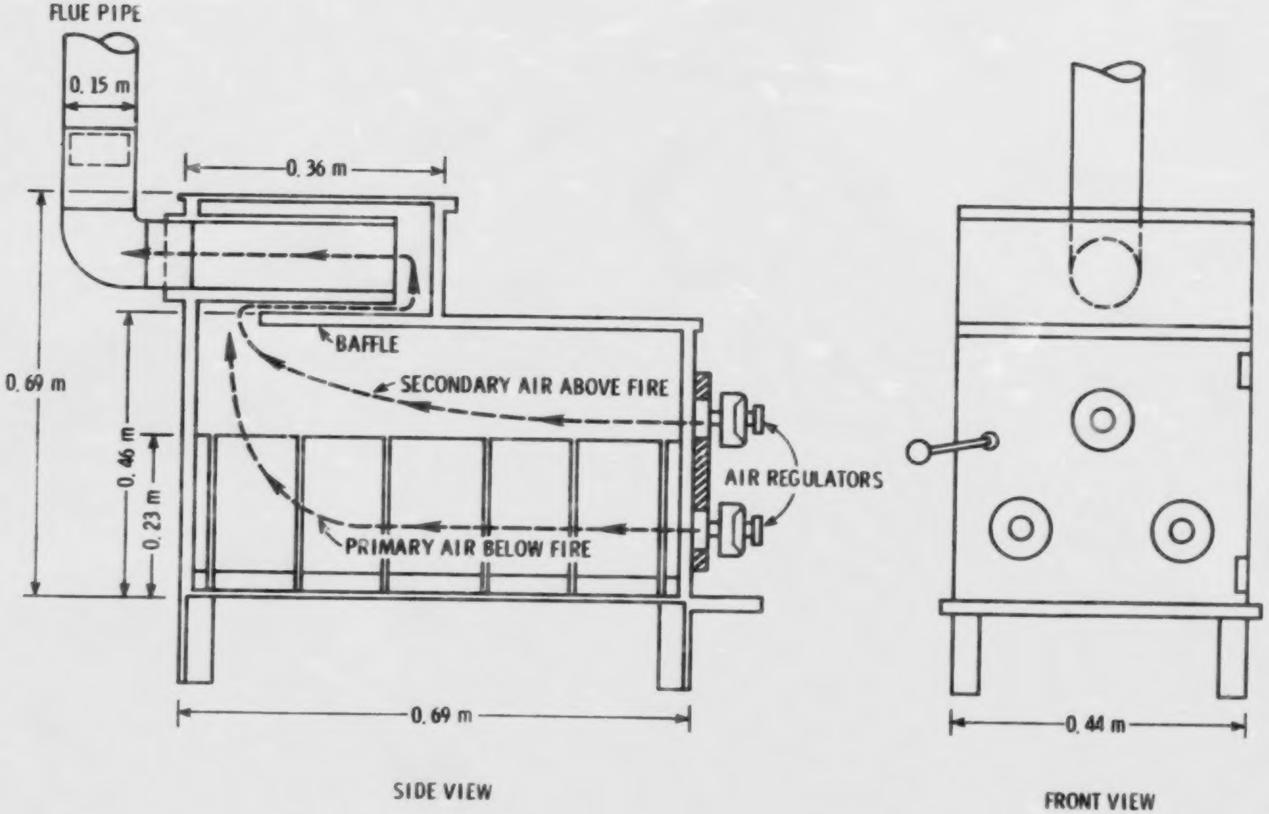
FLUE PIPE
0.15 m
0.36 m
0.69 m
0.46 m
0.23 m
BAFFLE
SECONDARY AIR ABOVE FIRE
AIR REGULATORS
PRIMARY AIR BELOW FIRE
0.69 m
0.44 m
SIDE VIEW
FRONT VIEW

Figure 2. Baffled air-tight stove showing primary and secondary combustion air flow pattern (8).

was lined with firebrick. The lower level of the top extended into the interior of the stove to form a baffle that required the smoke and exhaust gases to flow around to exit the unit. In addition, the flue pipe extended into the upper chamber created by the baffle. Thus, the exhaust from the combustion zone had to travel around two baffles in an "S" shaped flow pattern. Both primary and secondary combustion air entered through registers in the cast iron door. The baffled stove is somewhat unique in that it has three air regulators in the door rather than two as is common among other stoves of this type. The lower two air regulators are intended to supply primary combustion air while the upper inlet is intended to supply secondary air. This stove weighs approximately 200 kg (450 lb).

The nonbaffled stove is an air-tight, boiler plate radiant heater. The combustion zone dimensions are approximately 0.61 m high, 0.4 m wide and 0.71 m long. Two air inlets are located on the door of the stove. This unit, shown in Figure 3, weighs approximately 160 kg (350 lb). This unit was also lined with firebrick.

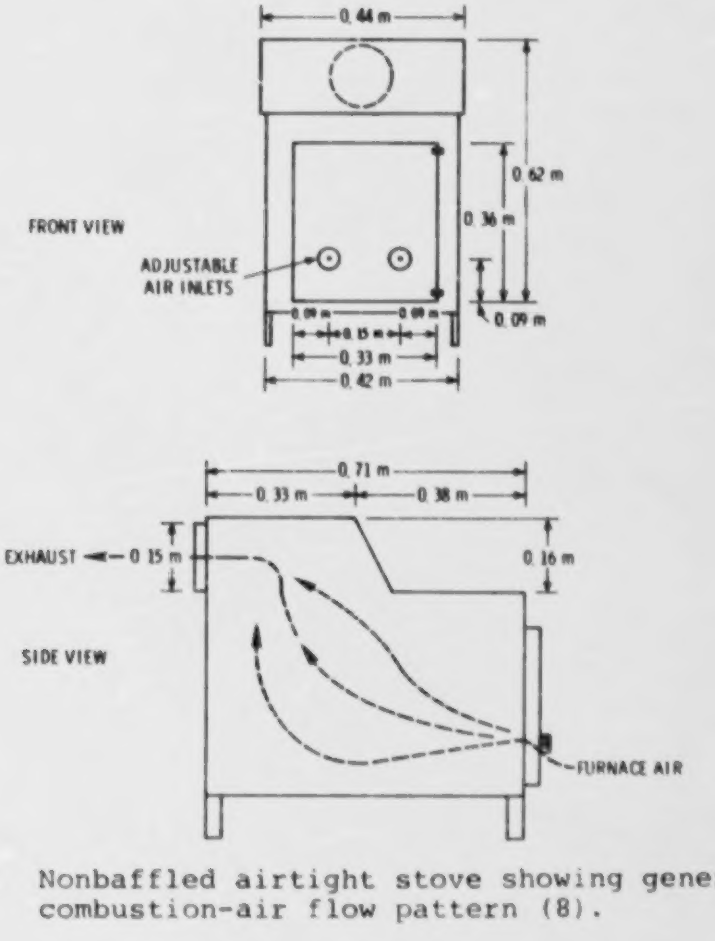
0.44 m
0.62 m
0.36 m
FRONT VIEW
ADJUSTABLE AIR INLETS
0.09 m
0.09 m
0.09 m
0.15 m
0.33 m
0.42 m
0.71 m
0.33 m
0.38 m
EXHAUST
0.15 m
0.16 m
SIDE VIEW
FURNACE AIR

Figure 3. Nonbaffled airtight stove showing generalized combustion-air flow pattern (8).

Each unit employed a 0.15 m (6-in.) flue pipe which discharged emissions into a roof vent as did the fireplace. The stoves were mounted on an electronic balance during testing to monitor wood combustion rates and to facilitate heat efficiency testing by Auburn University. The effect of sampling equipment on the balance readings was negligible because the sampling equipment was suspended by cables from piping and structural beams.

Each wood-burning stove was capable of accepting up to about 14 kg of split firewood. Heat release rates during testing ranged from 63,300 KJ/hr to 150,000 KJ/hr, while measured heat efficiency[a] ranged from 22% to 52%. The resultant rates for delivery of useful space heat are probably more representative for houses using wood as the primary heat source vis-a-vis secondary or auxillary space heating. Under different conditions of operation these values could have had even greater variance.

TEST WOOD

The selection of wood to be burned in the test equipment was based on availability and range of resin content. Oak and pine were chosen at the high and low moisture conditions represented by green wood and seasoned wood. Moisture content and heat release rate have been suggested as the two most important variables of the fuel wood that affect burning rate and, in turn, emission rates. Although the heating value (J/kg) of pine is not much different from that of oak, the heat release rate of pine is much greater because of its lower density and higher resin content.

Auburn University obtained the test wood from local sources. The green wood was cut several weeks prior to testing, and the seasoned wood was cut about 4 to 6 months prior to testing. The wood was obtained about 1 week before testing began and was stored indoors at the wood-burning laboratory.

The test wood was cut to lengths of about 0.5 m which occupied most of the length of the wood stove combustion chamber. Pieces larger than about 0.08 m in diameter were split to approximately that size. Samples of the unsplit wood were submitted to Industrial Testing Laboratory in St. Louis, Missouri, for proximate and ultimate analysis. The results of these tests are presented in Table 4. Moisture content is based on the wood as received and not on oven-dried wood as is often the case for data presented in the literature on wood. Moisture content was the only parameter that drastically changed from one sample to another, with green wood having 27% to 30% moisture and seasoned wood only 4% to 5% moisture. Relative to values reported in the literature

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[a] Useful heat recovered divided by the heat content of the wood burned.

(9, 10), the moisture content of the seasoned wood falls at the low extreme. Other parameters varied only slightly on a dry basis. Sulfur was found in the wood at a level of about 0.01%, which is approximately the detection limit of the sulfur determination technique.

TABLE 4. PROXIMATE AND ULTIMATE ANALYSIS OF WOOD USED IN THE TEST PROGRAM

Wood composition	Seasoned oak		Green oak		Seasoned pine		Green pine	
	As received	Dry basis	As received	Dry basis	As received	Dry basis	As received	Dry basis
Moisture,[a] %	4.25	-	27.07	-	5.16	-	29.61	-
Volatile matter, %	82.72	86.39	61.64	84.52	82.05	86.51	59.51	84.54
Fixed carbon, %	12.28	12.83	10.58	14.51	12.50	13.18	10.55	14.99
Ash, %	0.75	0.78	0.71	0.97	0.29	0.31	0.33	0.47
Sulfur, %	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Carbon, %	45.89	47.93	34.13	46.80	46.67	49.22	35.17	49.96
Hydrogen, %	6.29[b]	6.08	7.39[b]	6.01	6.35[b]	6.10	7.54[b]	6.04
Nitrogen, %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Oxygen, %	46.96[b]	45.10	57.66[b]	46.11	46.54[b]	44.26	56.85[b]	43.41
Heating[c] value,								
MJ/kg	17.9	18.7	13.4	18.3	18.2	19.2	13.6	19.4
Btu/lb	7,710	8,060	5,770	7,880	7,840	8,270	5,860	8,360

[a] Based on wood as received rather than oven dried wood. Moisture values reported in the literature are commonly based on oven dried wood.

[b] Includes that from moisture.

[c] High heating value. The high heating value neglects the heat used for vaporization of free and bound water formed during combustion.

TEST CONDITIONS

Operating conditions employed throughout the test program, in terms of quantity of wood charged and air flow rate through the combustion systems, were adequate to maintain good combustion. Charges of wood to all equipment were the maximum that could be accepted by each unit while maintaining reasonable combustion.

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(9) Soderstrom, N. Heating Your Home with Wood. Popular Science Skill Book, Times Mirror Magazines, Inc., New York, New York, 1978. 199 pp.

(10) Wood Chemistry, Second Edition, Volume 2, Wise, L. E., and E. C. Jahn, eds. Reinhold Publishing Co., New York, New York, 1974. pp. 475-479.

Thus 6 kg to 14 kg of wood was charged to each stove, and 4.5 kg to 10 kg was charged to the fireplace. Several charges of wood were allowed to burn before testing began to allow the equipment to reach thermal equilibrium and to establish a bed of coals in the combustion device. Initial startup, although possibly generating significant emissions, was not studied because of the difficulty in quantifying its contribution to the total burn covering at least several wood charges.

Combustion conditions were maintained in the air-tight stoves by manipulation of the air inlet vents until combustion was not excessive (flames reaching into the exhaust pipe) but also not starved for air (no visible flame present). Stack temperature was also used to aid in this control. The wood burning rate ranged from 6.0 kg/hr to 8.4 kg/hr. The fireplace was operated with glass doors open and damper fully open. The wood burning rate in the fireplace ranged from 9.6 kg/hr to 11 kg/hr. These burning rates are believed to be representative for wood stoves used for primary heating in the northern United States and for fireplaces. Wood stoves used for auxilary heating or for primary heating outside the north will have lower burning rates.

Emission sampling was conducted after at least four charges of wood had burned. Grab samples, as in the case of NO_x and CO, were taken at various stages of the burn cycle and from different wood charges. Integrated sampling, such as EPA-5, POM train, and SASS train sampling, was conducted during the combustion of a minimum of one charge of wood and often during combustion of two or more wood charges. Sampling equipment operation was therefore maintained during the charging of a load of wood to the combustion equipment. No other disturbances to the fuel bed took place except for an occasional manipulation of the fuel bed to prevent smothering the fire, and this was kept to a minimum. Ash or combustion residue was not removed during testing but remained in the combustion equipment overnight to allow combustion to approach completion and to permit handling of the ash for sample collection.

SAMPLING METHODS AND EQUIPMENT

Sampling methods and equipment were selected on the basis of the type and quality of data required, the physical arrangement of the test site, and the nature of the combustion process. The specific techniques employed for collecting each pollutant in this program are described below.

Particulate and Condensable Organics

The procedure and equipment used for the quantitative particulate collection meet specifications outlined in Method 5 of the Federal

Register (11). Previous studies on coal-fired residential heating devices have indicated a flat velocity profile across the stack (12). Because of the small stack diameters (0.15 m and 0.20 m), single-point sampling was used to determine the mass emission rates with the probe tip placed in the center of the exhaust stack.

Mass emissions were collected over a period of 45 min to 120 min, corresponding to sampling volumes of approximately 0.6 Nm^3 (normal cubic meters) to 1.7 Nm^3 of stack gas. Emissions from the airtight stoves produced high mass loadings and resulted in the shorter sampling times and collection of less than the recommended sample volume of 1.7 Nm^3. Sampling was initiated after several charges of wood had burned and continued through at least one additional charge of wood.

Probe tip selection was based on the desire to have extended sampling times and the need for isokinetic sampling. Because of the cyclic nature of the combustion process, the temperature at the point of sampling varied by as much as 280°C. Rather than use average stack temperatures to determine sampling parameters such as the κ factor[a] (see reference 13 for the function of the κ factor), the temperature at each reading (5-min intervals) was used to determine a new κ factor. Figure 4 is a reproduction of a graph employed in the field for κ factor determination.

Particulate emissions were also measured with the POM train and the SASS train discussed later in this section.

Condensable organic material was determined from the back-half portion of the Method 5 sampling train (Figure 5). The back half of the train consists of water-filled impingers that collect most materials passing through the front-half filter. This material

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[a] κ factor is a proportionality factor relating stack velocity measurement pressure differential and gas meter orifice pressure differential to obtain isokinetic sampling.

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(11) Environmental Protection Agency - Part II - Standards of Performance for New Stationary Sources - Revision to Reference Method 1-8. Method 5 - Determination of Particulate Emissions from Stationary Sources. Federal Register, 42(160):41776-41782, August 1977.

(12) DeAngelis, D. G., and R. B. Reznik. Source Assessment: Coal-Fired Residential Combustion Equipment Field Tests. EPA-600/2-78-004c, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1977. 81 pp.

(13) Yergovich, T. W. Development of a Practical Source Sampling Slide Rule. Journal of the Air Pollution Control Association, 26(6):590-592, 1976.

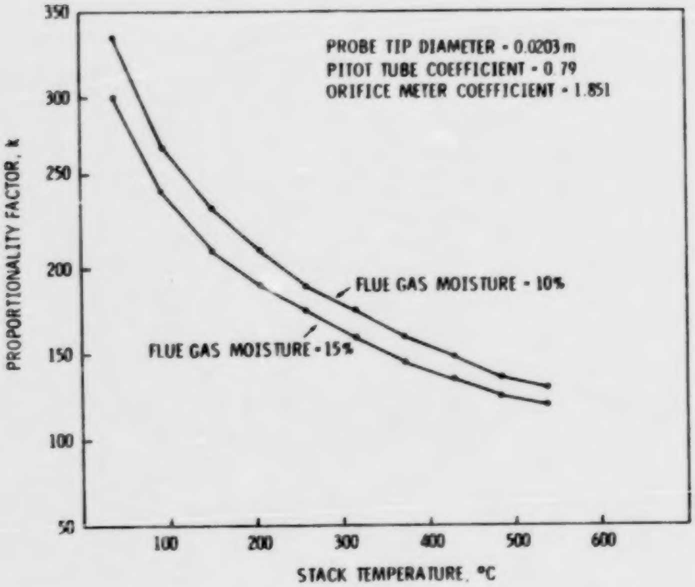

Figure 4. EPA Method 5 train proportionality factor (κ) versus stack temperature for several flue gas moisture contents.

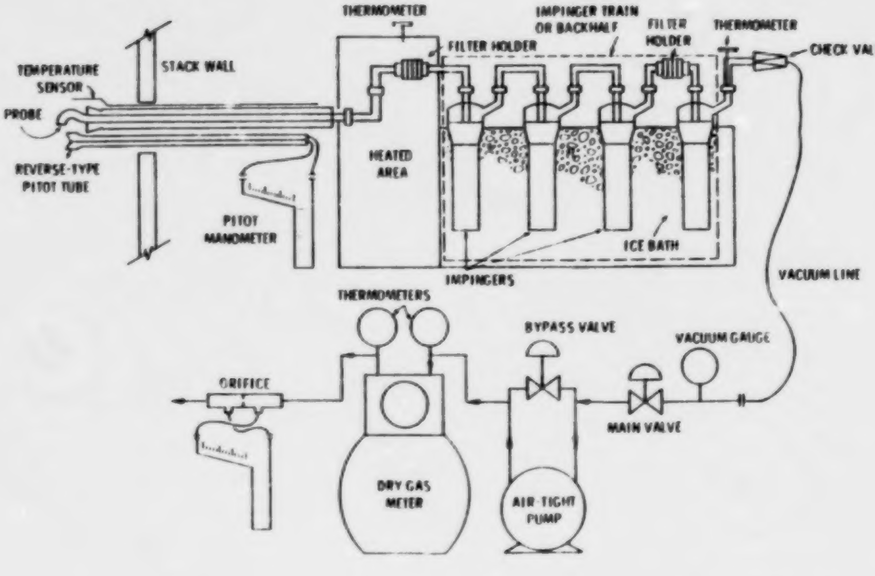
THERMOMETER
IMPINGER TRAIN OR BACKHALF
FILTER HOLDER
THERMOMETER
CHECK VALVE
FILTER HOLDER
TEMPERATURE SENSOR
STACK WALL
PROBE
REVERSE-TYPE PITOT TUBE
HEATED AREA
PITOT MANOMETER
ICE BATH
IMPINGERS
VACUUM LINE
THERMOMETERS
BYPASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
DRY GAS METER
AIR-TIGHT PUMP

Figure 5. Schematic of EPA Method 5 sampling train with back-up filter for particulate and condensable organic material collection.

is sometimes considered a part of the total sample. In addition, a back-up filter was inserted between the third and fourth impinger. A previous study on fireplase emissions employing a back-up filter found that a significant mass collected on this filter (1). This same study showed that the back half of the Method 5 train and back-up filter contained from 50% to 80% of the total material collected when sampling fireplace emissions. This material has been observed to be an organic-type residue.

In this study the material collected in the back half of the EPA Method 5 train accounted for 54% to 76% of the total mass collected; 12% to 39% of the back-half mass was collected on the back-up filter.

The impinger solutions were observed to range from yellow to light brown in color, while the back-up filter catches were consistently yellow. No phase separation was observed. Connecting glassware was dotted with brown resinous material which proved difficult to recover. Final cleaning of glassware was accomplished by soaking in acetone.

Sulfur Oxides

Although sulfur oxide emissions were expected to be low from residential wood burning devices, two measurements employing EPA Method 6 were made (14). Analysis of the test wood indicated little or no variation in sulfur by wood type. Emission tests for SO_2 were run on combustion of seasoned oak and seasoned pine in an airtight stove. Fireplace emissions of SO_2 would be less concentrated and more difficult to detect.

Nitrogen Oxides

EPA Method 7 was employed, as specified in the Federal Register (15), to determine emissions of nitrogen oxides. Because this is a grab sample method, six samples were taken at each test condition. These were collected over a period of time long enough to obtain samples during the burn of several wood charges and representing various stages of the burning cycle. Each sample consisted of about 2 L of flue gas collected over 30 s.

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(14) Environmental Protection Agency - Part II - Standards of Performance for New Stationary Sources - Revision to Reference Method 1-8. Method 6 - Determination of Sulfur Dioxide Emissions from Stationary Sources. Federal Register, 41(111):23083-23085, August 1977.

(15) Environmental Protection Agency - Part II - Standards of Performance for New Stationary Sources - Revision to Reference Method 1-8. Method 7 - Determination of Nitrogen Oxide Emissions from Stationary Sources. Federal Register, 42(160):41784-41796, August 1977.

Carbon Monoxide, Oxygen, and Carbon Dioxide

Concentrations of carbon monoxide (CO), oxygen (O_2), and carbon dioxide (CO_2) in the flue gas were determined as directed under EPA Method 3 employing the Orsat technique (16). These measurements were performed as part of the heat efficiency testing conducted by Auburn University. Ten grab samples were collected for analysis during the burning of one charge of wood. These values provide a profile of the change in flue gas composition during a burning cycle, and their average provides the average CO composition for determination of emission rates, expressed as grams of pollutant emitted per kilogram of wood burned.

Because the fireplace employs excessive dilution air, the flue gas concentrations of CO were below the detection limit of the Orsat technique. Therefore, Tedlar bag samples were collected over 15-min to 30-min intervals and analyzed with Dräger tubes (17). Dräger tubes are normally used in workplace environments where it is necessary to determine very small concentrations of CO in ambient air with maximum reliability in a short time. Tubes are packed with a reagent that reacts when contacted with CO to produce a color change. The volume of reagent changing color indicates the volume of CO present in a fixed volume of sample.

The Dräger tube employed (carbon monoxide 10/b) contains a precleanse layer that retains interfering gases (e.g., petroleum distillates, benzene, hydrogen sulfide). Acetylene and hydrogen in concentrations greater than 50% are indicated as CO but were not a problem in this program. The detection range of the tube was from 100 parts per million (ppm) to 3,000 ppm with a relative standard deviation of 10% to 15% (17).

Low Molecular Weight Hydrocarbons

The C_1-C_6 hydrocarbon emissions were sampled and analyzed on site. Flue gas samples were collected in Tedlar bags for analysis by gas chromatography. The samples were analyzed by the Varian 1400 gas chromatography-flame ionization detector with temperature programming capabilities. Breathing air and high purity hydrogen were used to sustain the flame, and prepurified nitrogen was used as the carrier gas.

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(16) Environmental Protection Agency - Part II - Standards of Performance for New Stationary Sources - Revision to Reference Method 1-8. Method 3 - Gas Analyses for Carbon Dioxide, Excess Air, and Dry Molecular Weight. Federal Register, 42(160):41768-41771, August 1977.

(17) Detector Tube Handbook, Air Investigations, and Technical Gas Analysis with Dräger Tubes, 2nd Edition, compiled by Kurt Liechnitz. Drägerwerk AG, Lubeck, Federal Republic of Germany, October 1973. 164 pp.

The column employed was the Chromosorb 102 (1.8 m long x 3.2 x 10^{-3} m I.D.). The column oven was programmed to run from 50°C to 150°C at 20°C/minute. This was a sufficient temperature range to chromatograph all the hydrocarbon components.

Samples of stack gas were injected into a 1-mL sample loop and directed from the loop to the column by the carrier gas. The gas separates in the column and is sent to the flame ionization detector where an electrical signal proportional to the concentration of hydrocarbons present actuates a strip chart recorder for permanent record keeping.

A stopwatch was used to determine the exact time each hydrocarbon component was separated. Standard gas peaks were also timed to match these against the unknown hydrocarbons for species identification. Peak heights were measured on the hydrocarbon unknowns and compared against the peak heights of the standards to determine the relative concentration of the unknowns.

This method is sensitive to hydrocarbons in the C_1-C_5 range from 10 ppm to 10,000 ppm.

Formaldehyde and Other Aldehydes

No standard methods have been developed for sampling aldehydes in stack gas emissions. The method employed in this program is designed for ambient air sampling as reported in Reference 18. The method was modified for stack gas sampling by drawing flue gas through a 10% aqueous sodium bisulfite solution ($NaHSO_3$). The sampling apparatus included a glass probe with a plug of glass wool to filter out particulates, two midget impingers containing 10 mL of 10% aqueous sodium bisulfite solution ($NaHSO_3$), an empty impinger, a pump, a flowmeter, and a dry test meter. Sampling was conducted at a rate of 2 L/min for a period of 15 min to 30 min. A diagram of the sampling system is shown in Figure 6.

After sample collection, the impinger contents were transferred to a 100-mL sample bottle. The glass wool plug was removed and discarded. All glassware from the probe to the dry impinger was rinsed with three portions of 10% $NaHSO_3$, and the rinses were added to the sample bottle.

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(18) Methods of Air Sampling and Analysis. American Public Health Association, Washington, D.C., 1972. pp. 190-198.

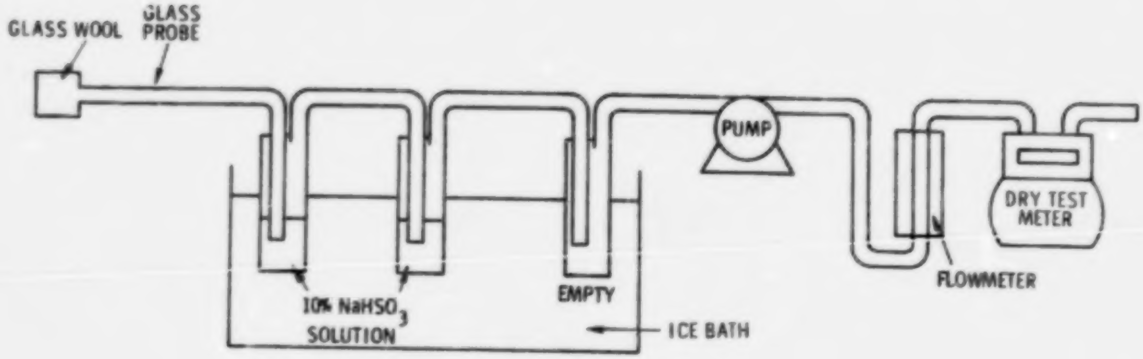
GLASS WOOL
GLASS PROBE
PUMP
DRY TEST METER
FLOWMETER
10% NaHSO3 SOLUTION
EMPTY
ICE BATH

Figure 6. Diagram of sampling train for aldehydes.

POM Screening

An ultraviolet (UV) fluorescence technique for detection of POM compounds has been reported by Smith & Levins (19). This technique was employed in this program for field screening. Samples for screening were collected in a midget impinger train containing methylene chloride. Figure 7 illustrates the setup of this train.

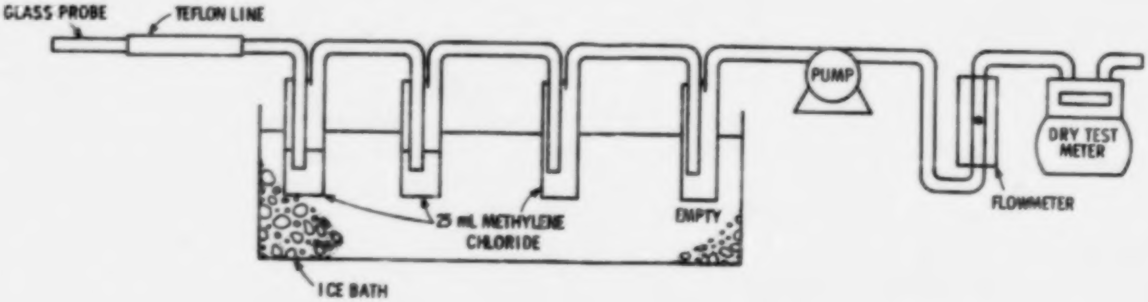
GLASS PROBE
TEFLON LINE
PUMP
DRY TEST METER
FLOWMETER
25 mL METHYLENE CHLORIDE
EMPTY
ICE BATH

Figure 7. Diagram of sampling train for POM screening.

Approximately 0.014 m^3 of flue gas were collected over a period of about 45 minutes in this train. Loss of methylene chloride during sampling due to evaporation amounted to about 15 mL (20%). It was observed at the completion of a run that the first impinger contents were a light yellow color while the contents of the third impinger were nearly clear. To prevent dilution of the overall sample, the contents of the third impinger were used to make three successive rinses of the probe assembly. All impinger contents and rinses were combined in a Level I cleaned (20) glass bottle.

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(19) Smith, E. M., and P. L. Levins. Sensitized Fluorescence for the Detection of Polycyclic Aromatic Hydrocarbons. EPA-600/7-78-182, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, September 1978. 31 pp.

Screening for POM's was performed by employing the basic technique reported by Smith & Lewis (19). One microliter of the combined train sample was spotted twice onto a clean Whatman filter using a microcapillary tube. One spot was treated with 1 μL of a naphthalene solution (60 mg/L) to increase the sensitivity of that spot to UV fluorescence. Naphthalene was also spotted alone as a blank and its intensity, when fluorescent, was subjectively subtracted from the sample intensity. It was determined in the laboratory that reagent-grade naphthalene often contains contaminants that fluoresce under UV light. Figure 8 illustrates the spotting arrangement of the samples and naphthalene blank.

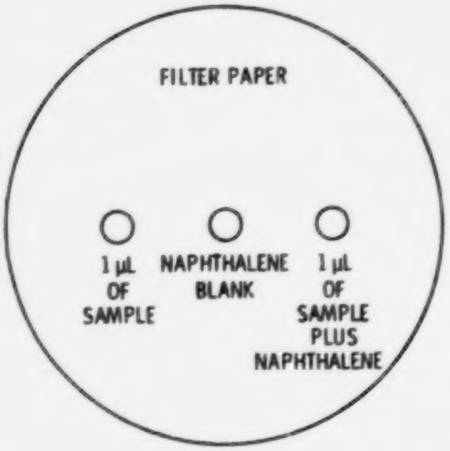

Figure 8. Arrangement of sample spots and blank on filter paper for POM screening.

The spotted filter paper was inserted into a box containing the UV light source where the fluorescence was observed visually and recorded. Subjective visual adjustment was made when the naphthalene blank also fluoresced.

Table 5 presents the calibration of the technique as determined via benzo(a)pyrene standard.

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(20) Hamersma, J. W., S. L. Reynolds, and R. F. Maddalone. IERL-RTP Procedure Manual: Level I Environmental Assessement. EPA-600/1-76-160a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1976. 147 pp.

TABLE 5. CALIBRATION OF POM SPOT TEST

Visual observation		Approximate mass of POM's in spot, pg
Spot without sensitizer	Spot with sensitizer	
Fluorescent	Strong fluorescence	≥1,000
None	Strong fluorescence	100 - 1,000
None	Weak fluorescence	10 - 100
None	None	≤10

POM and Other Organic Species by POM Train

A modified Method 5 procedure was used to obtain samples of particulate, POM, and other organic emissions. The modification added an XAD-2 resin trap between the filter and impinger system of the standard Method 5 train to collect organic species. A cooler trap was inserted between the filter and the resin trap to reduce the gas temperature to 21°C before its entry into the resin trap. The remaining impingers were made up according to the EPA Method 5 procedure (11).

At the completion of a sampling run, the resin trap was removed and capped. The entire train, from probe tip to filter holder, was cleaned with methylene chloride and the sample was bottled in amber glass. Cooler trap contents were measured, and the liquid was poured into an amber bottle. Contents of the water impingers were also measured in order to determine the quantity of condensed water, and the contents were stored in a separate amber bottle. The silica gel impinger contents were weighed, and the material discarded. All samples were stored in a refrigerator on site and delivered to MRC's Dayton Laboratory on ice.

This system also determined particulate emissions in accordance with the standard Method 5 procedure since the front-half of the train remained unchanged.

The basic Method 5 schematic was shown earlier in Figure 5. Figure 9 shows the components and sample recovery procedure for the modification.

Operation of this train parallels that discussed earlier for the EPA Method 5 train in terms of sample volume, sampling time and other operating procedures.

SASS Train Samples

The SASS train employed in the environmental assessment portion of this study was used to sample for particulate loading,

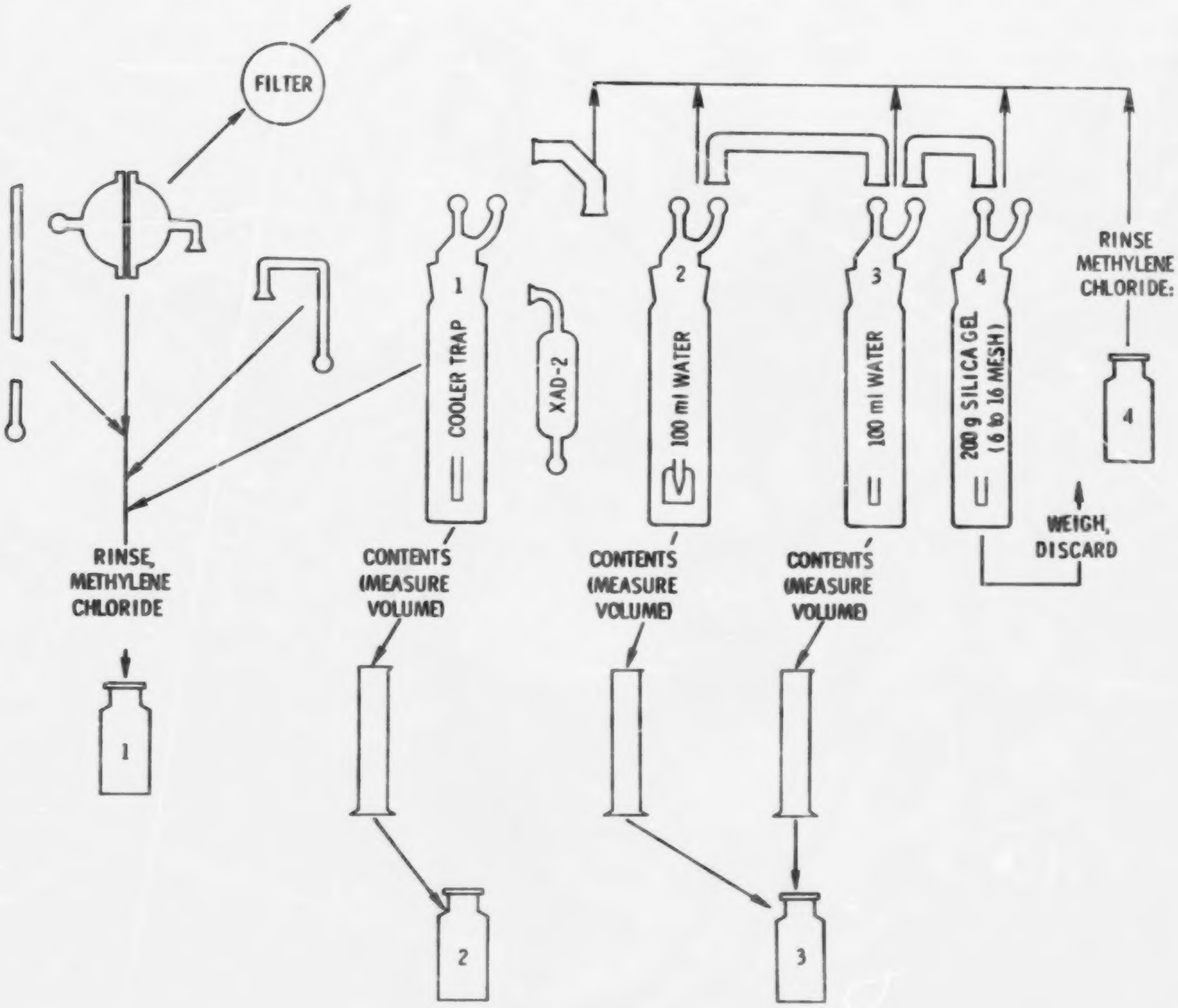
FILTER
1
COOLER TRAP
XAD-2
2
100 ml WATER
3
100 ml WATER
4
200 g SILICA GEL (6 to 16 MESH)
RINSE METHYLENE CHLORIDE:
4
WEIGH, DISCARD
RINSE, METHYLENE CHLORIDE
CONTENTS (MEASURE VOLUME)
CONTENTS (MEASURE VOLUME)
CONTENTS (MEASURE VOLUME)
1
2
3

Figure 9. Schematic of POM train components and sample recovery.

particle size data, organic compounds including POM's, individual elements, and bioassay samples. The SASS train system, depicted in Figure 10 (20), employs a set of three cyclones and a filter for particle size fractionation, a solid sorbent (XAD-2) trap, for organic species, a trace inorganic impinger trap, and a system for flow measurement and gas pumping. The SASS train is a high volume sampler which collects sufficient sample for inorganic and organic analysis of emissions species that are undetected in conventional systems.

The SASS train sampled inorganic and organic emissions simultaneously. Inorganic species were primarily collected by the cyclones and filters. Volatile inorganics were also collected in the solid sorbent trap and the impinger solutions. Organic species were primarily collected in the solid sorbent trap, although other portions of the train (particulate samples, impinger solutions, and rinse solutions) are solvent extracted to recover any other organic material. It is believed that organic species greater than C_6 in molecular weight will be retained in the adsorber trap, and compounds in the C_1-C_6 molecular weight range will pass through the system without being trapped.

The impinger portion of the train consists of four impingers. The impinger order, impinger contents, and purpose of each impinger are shown in Table 6. In the collection of samples for bioassay, the impingers were charged only with water and discarded at the conclusion of each test after volume change had been recorded.

TABLE 6. SASS TRAIN IMPINGER SYSTEM FOR TRACE ELEMENTS (20)

Impinger	Reagent	Quantity	Purpose
1	30% H_2O_2	750 mL	Trap reducing gases such as SO_2 to prevent depletion of oxidative capability of trace-element-collecting impingers 2 and 3.
2	0.2 M $(NH_4)_2S_2O_8$ + 0.02 M $AgNO_3$	750 mL	Collection of volatile trace elements by oxidative dissolution.
3	0.2 M $(NH_4)_2S_2O_8$ + 0.02 M $AgNO_3$	750 mL	Collection of volatile trace elements by oxidative dissolution.
4	3-8 Mesh silica gel (color indicating)	750 g	Prevent moisture from reaching pumps.

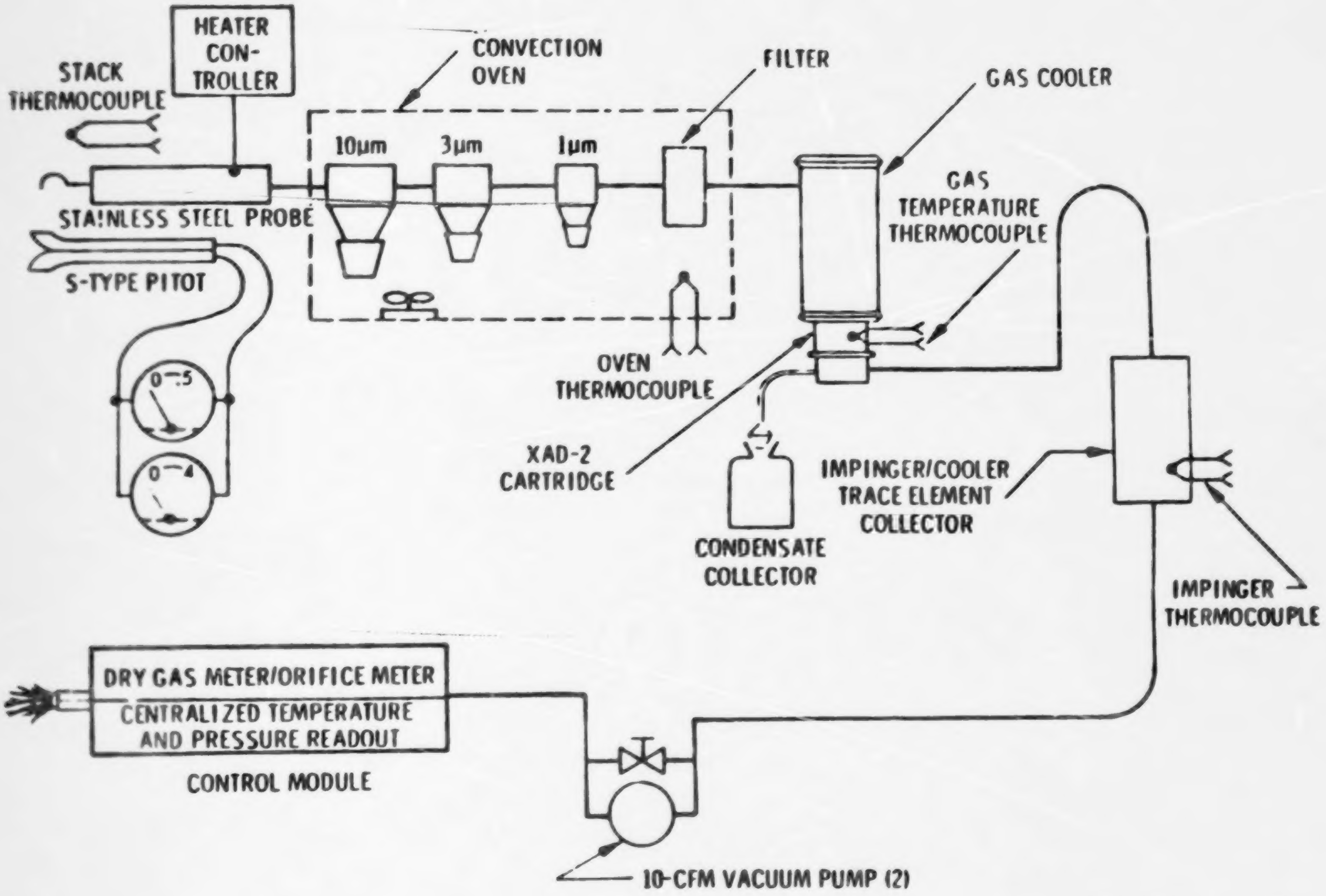
HEATER CON-TROLLER
STACK THERMOCOUPLE
CONVECTION OVEN
FILTER
GAS COOLER
10μm
3μm
1μm
STAINLESS STEEL PROBE
S-TYPE PITOT
GAS TEMPERATURE THERMOCOUPLE
0—.5
0—4
OVEN THERMOCOUPLE
XAD-2 CARTRIDGE
CONDENSATE COLLECTOR
IMPINGER/COOLER TRACE ELEMENT COLLECTOR
IMPINGER THERMOCOUPLE
DRY GAS METER/ORIFICE METER
CENTRALIZED TEMPERATURE AND PRESSURE READOUT
CONTROL MODULE
10-CFM VACUUM PUMP (2)

Figure 10. Schematic of source assessment sampling system (20).

Before sampling, the SASS train components were passivated with 1:1 (on a volume basis) aqueous nitric acid. All surfaces associated with organic collection were cleaned with distilled water, isopropyl alcohol, and methylene chloride in succession. These components were dried with a stream of clean air or nitrogen. Impingers were cleaned first with distilled water and then with isopropyl alcohol.

At the site, the train was assembled, and the oven was heated to 205°C before each run. The resin trap was maintained at 20°C during a run. A leak check was made before and after each run; a leak rate less than 0.0014 m^3 per minute at 508 mm Hg was considered acceptable.

The suggested sample volume of 30 m^3 became unrealistic in this program for several reasons. The first attempt at a SASS train run took approximately 7 hours excluding startup and leak checks, and required three filter changes due to high loading. The accumulation of condensed organic material on inner surfaces of the train was so severe that clean-up time doubled and required soaking components in methylene chloride overnight to recover the sample. Approximately 2 to 3 times the expected volume of methylene chloride was used to recover the sample and clean the train. This, coupled with the potential risk involved in handling highly concentrated pollutants, resulted in the decision to sample only 15 m^3 of flue gas. Although organic buildup remained greater than desired, the situation was manageable. The large sample volumes did require more time to process, especially in laboratory extraction and separation. The basic SASS train sample recovery and clean-up procedures are specified in the Level I Procedures Manual[a] and shown in Figures 11 to 13 (20). Figure 12 differs from the recommended procedure for cleanup of the XAD-2 module in that the condensate is usually extracted with methylene chloride in the field. The decision to omit this step was made after the first SASS run when, upon extraction of the condensate, it was observed that the extraction step was not removing a significant fraction of the organic material based on color. After discussion with the EPA, it was decided that a more complex laboratory extraction was needed, and that the condensate should be collected in an amber bottle, properly preserved and transported to MRC with the remaining samples.

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[a] The field study conducted in this program took place prior to publication of the revised Level I Procedures Manual (20); however, some procedural changes were transmitted from EPA to MRC by phone during the field study.

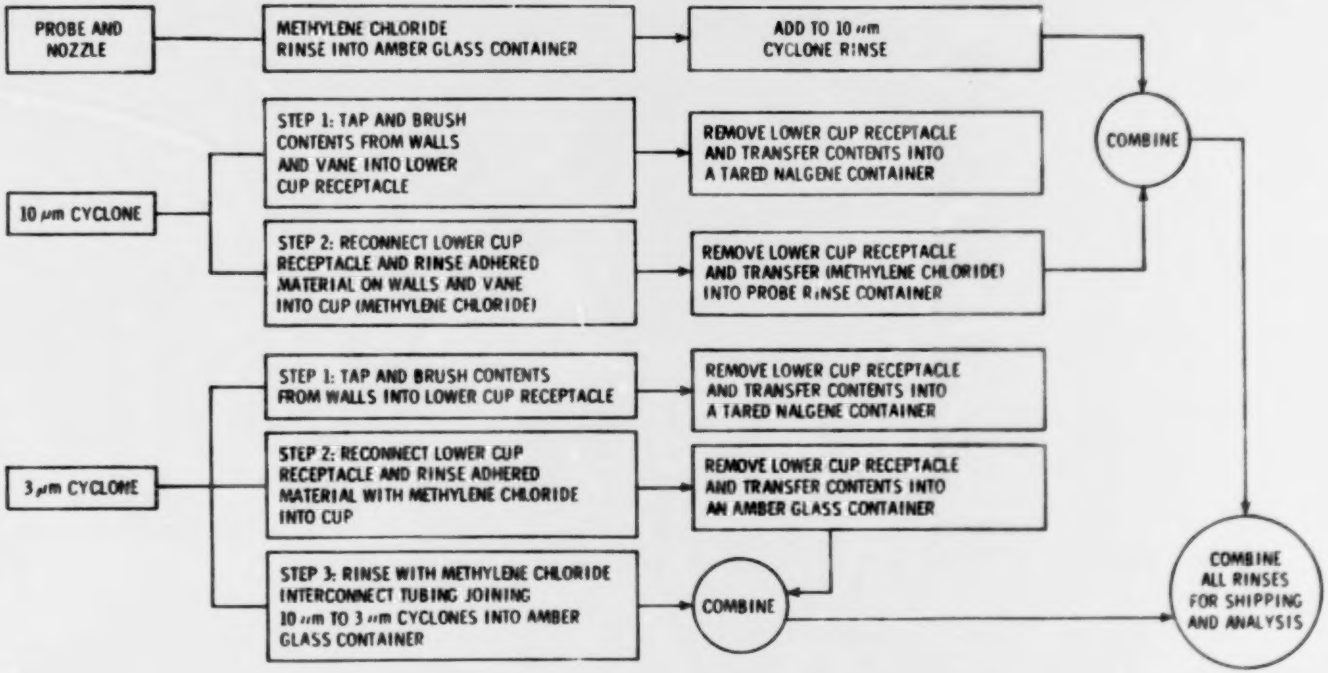
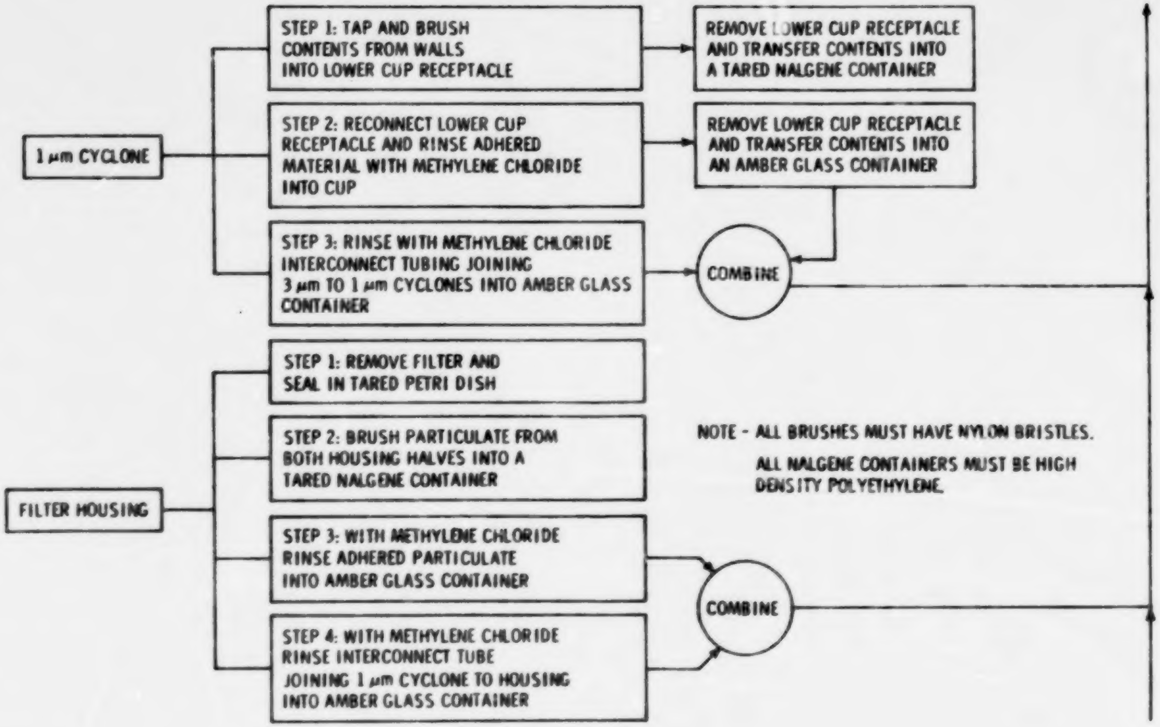

PROBE AND NOZZLE
METHYLENE CHLORIDE RINSE INTO AMBER GLASS CONTAINER
ADD TO 10 μm CYCLONE RINSE
10 μm CYCLONE
STEP 1: TAP AND BRUSH CONTENTS FROM WALLS AND VANE INTO LOWER CUP RECEPTACLE
REMOVE LOWER CUP RECEPTACLE AND TRANSFER CONTENTS INTO A TARED NALGENE CONTAINER
COMBINE
STEP 2: RECONNECT LOWER CUP RECEPTACLE AND RINSE ADHERED MATERIAL ON WALLS AND VANE INTO CUP (METHYLENE CHLORIDE)
REMOVE LOWER CUP RECEPTACLE AND TRANSFER (METHYLENE CHLORIDE) INTO PROBE RINSE CONTAINER
3 μm CYCLONE
STEP 1: TAP AND BRUSH CONTENTS FROM WALLS INTO LOWER CUP RECEPTACLE
REMOVE LOWER CUP RECEPTACLE AND TRANSFER CONTENTS INTO A TARED NALGENE CONTAINER
STEP 2: RECONNECT LOWER CUP RECEPTACLE AND RINSE ADHERED MATERIAL WITH METHYLENE CHLORIDE INTO CUP
REMOVE LOWER CUP RECEPTACLE AND TRANSFER CONTENTS INTO AN AMBER GLASS CONTAINER
STEP 3: RINSE WITH METHYLENE CHLORIDE INTERCONNECT TUBING JOINING 10 μm TO 3 μm CYCLONES INTO AMBER GLASS CONTAINER
COMBINE
COMBINE ALL RINSES FOR SHIPPING AND ANALYSIS

Figure 11. Sample handling and transfer-nozzle, probe, cyclones, and filter (20).

(continued)


1 µm CYCLONE
STEP 1: TAP AND BRUSH CONTENTS FROM WALLS INTO LOWER CUP RECEPTACLE
REMOVE LOWER CUP RECEPTACLE AND TRANSFER CONTENTS INTO A TARED NALGENE CONTAINER
STEP 2: RECONNECT LOWER CUP RECEPTACLE AND RINSE ADHERED MATERIAL WITH METHYLENE CHLORIDE INTO CUP
REMOVE LOWER CUP RECEPTACLE AND TRANSFER CONTENTS INTO AN AMBER GLASS CONTAINER
STEP 3: RINSE WITH METHYLENE CHLORIDE INTERCONNECT TUBING JOINING 3 µm TO 1 µm CYCLONES INTO AMBER GLASS CONTAINER
COMBINE
FILTER HOUSING
STEP 1: REMOVE FILTER AND SEAL IN TARED PETRI DISH
STEP 2: BRUSH PARTICULATE FROM BOTH HOUSING HALVES INTO A TARED NALGENE CONTAINER
STEP 3: WITH METHYLENE CHLORIDE RINSE ADHERED PARTICULATE INTO AMBER GLASS CONTAINER
STEP 4: WITH METHYLENE CHLORIDE RINSE INTERCONNECT TUBE JOINING 1 µm CYCLONE TO HOUSING INTO AMBER GLASS CONTAINER
COMBINE

NOTE - ALL BRUSHES MUST HAVE NYLON BRISTLES.
ALL NALGENE CONTAINERS MUST BE HIGH DENSITY POLYETHYLENE.

Figure 11 (continued)

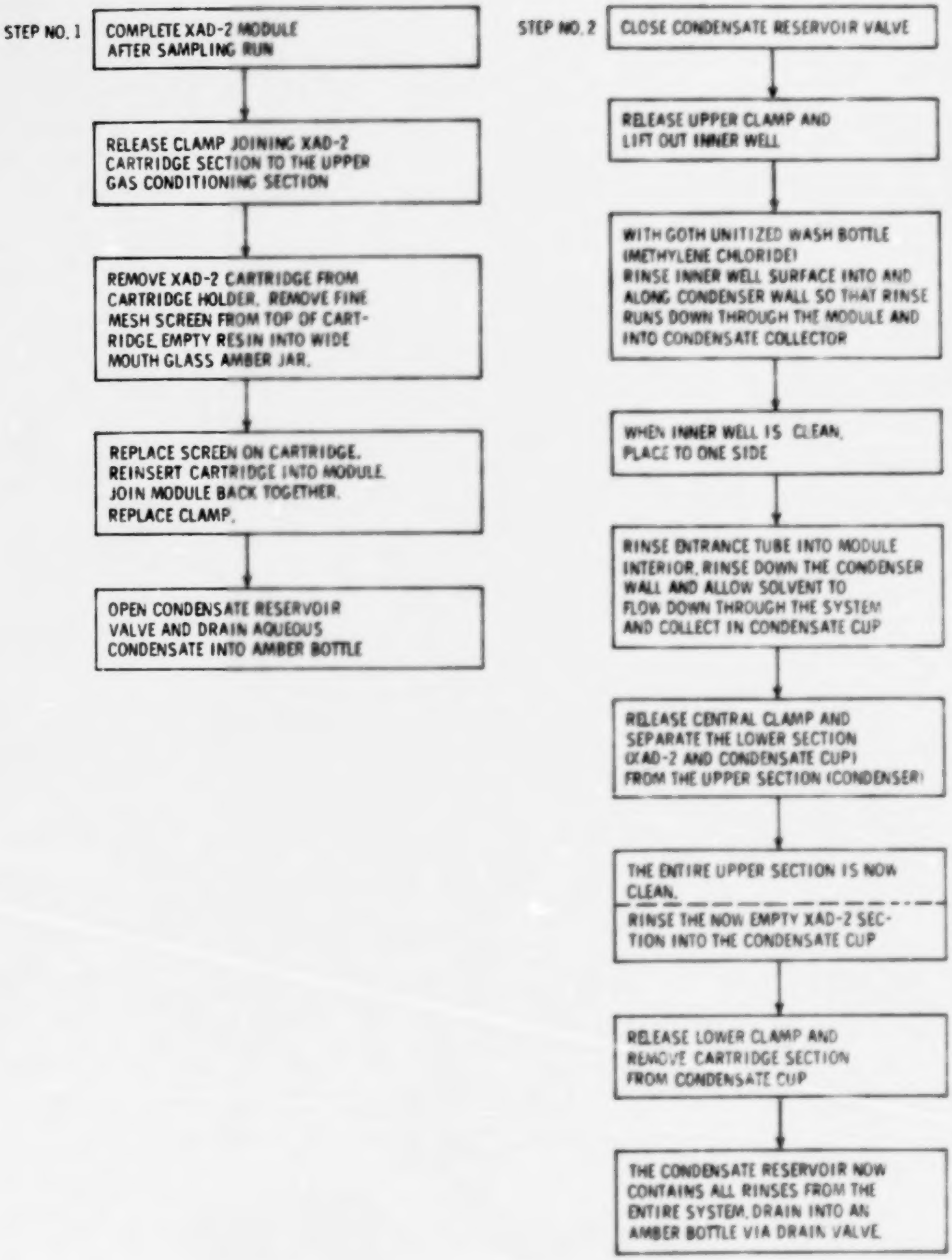

STEP NO. 1
COMPLETE XAD-2 MODULE AFTER SAMPLING RUN
RELEASE CLAMP JOINING XAD-2 CARTRIDGE SECTION TO THE UPPER GAS CONDITIONING SECTION
REMOVE XAD-2 CARTRIDGE FROM CARTRIDGE HOLDER. REMOVE FINE MESH SCREEN FROM TOP OF CARTRIDGE. EMPTY RESIN INTO WIDE MOUTH GLASS AMBER JAR.
REPLACE SCREEN ON CARTRIDGE. REINSERT CARTRIDGE INTO MODULE. JOIN MODULE BACK TOGETHER. REPLACE CLAMP.
OPEN CONDENSATE RESERVOIR VALVE AND DRAIN AQUEOUS CONDENSATE INTO AMBER BOTTLE
STEP NO. 2
CLOSE CONDENSATE RESERVOIR VALVE
RELEASE UPPER CLAMP AND LIFT OUT INNER WELL
WITH GOTH UNITIZED WASH BOTTLE (METHYLENE CHLORIDE) RINSE INNER WELL SURFACE INTO AND ALONG CONDENSER WALL SO THAT RINSE RUNS DOWN THROUGH THE MODULE AND INTO CONDENSATE COLLECTOR
WHEN INNER WELL IS CLEAN, PLACE TO ONE SIDE
RINSE ENTRANCE TUBE INTO MODULE INTERIOR. RINSE DOWN THE CONDENSER WALL AND ALLOW SOLVENT TO FLOW DOWN THROUGH THE SYSTEM AND COLLECT IN CONDENSATE CUP
RELEASE CENTRAL CLAMP AND SEPARATE THE LOWER SECTION (XAD-2 AND CONDENSATE CUP) FROM THE UPPER SECTION (CONDENSER)
THE ENTIRE UPPER SECTION IS NOW CLEAN.
RINSE THE NOW EMPTY XAD-2 SECTION INTO THE CONDENSATE CUP
RELEASE LOWER CLAMP AND REMOVE CARTRIDGE SECTION FROM CONDENSATE CUP
THE CONDENSATE RESERVOIR NOW CONTAINS ALL RINSES FROM THE ENTIRE SYSTEM. DRAIN INTO AN AMBER BOTTLE VIA DRAIN VALVE

Figure 12. Sample handling and transfer - XAD-2 module (20).

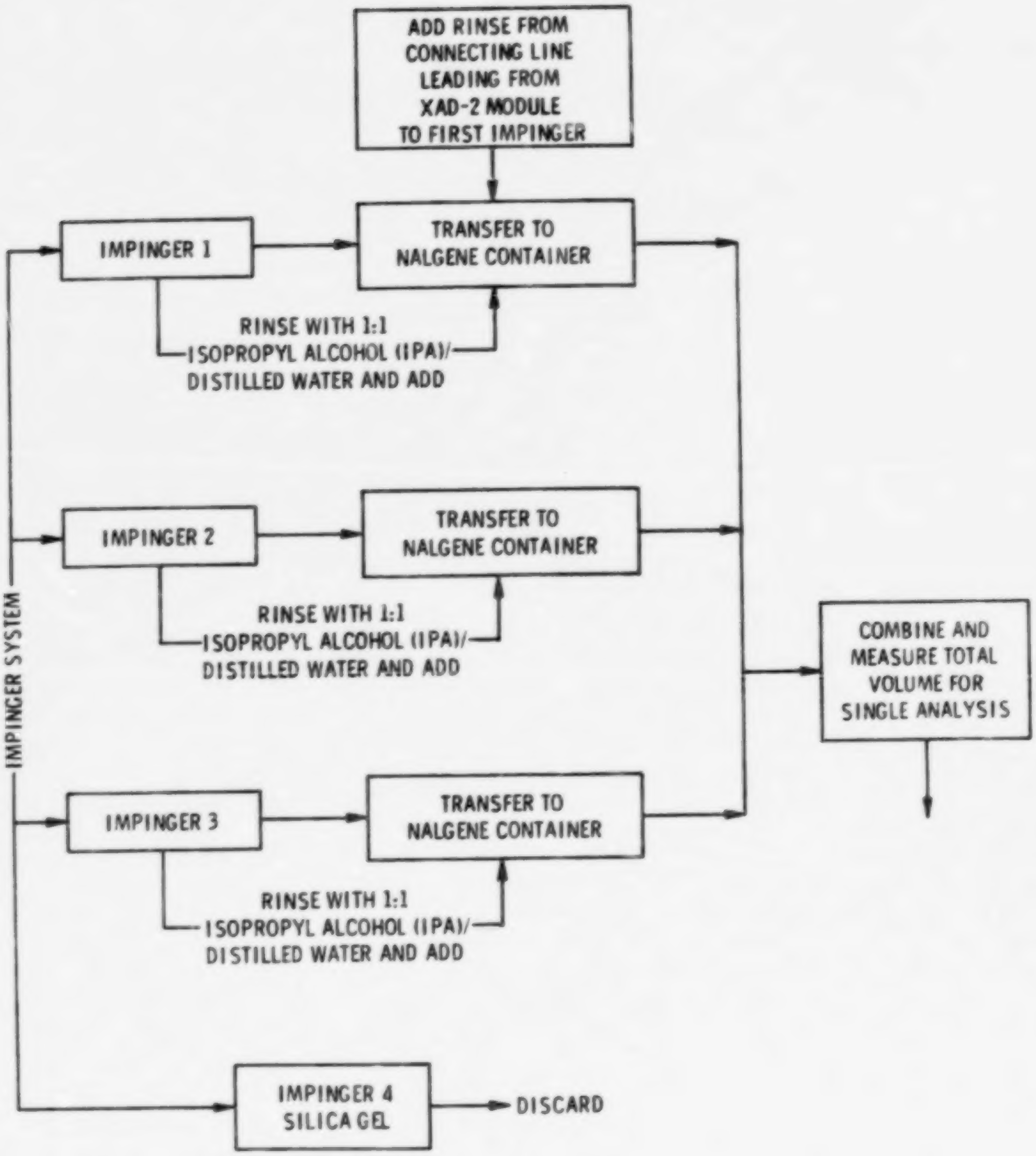

ADD RINSE FROM CONNECTING LINE LEADING FROM XAD-2 MODULE TO FIRST IMPINGER
IMPINGER 1
TRANSFER TO NALGENE CONTAINER
RINSE WITH 1:1 ISOPROPYL ALCOHOL (IPA)/ DISTILLED WATER AND ADD
IMPINGER 2
TRANSFER TO NALGENE CONTAINER
RINSE WITH 1:1 ISOPROPYL ALCOHOL (IPA)/ DISTILLED WATER AND ADD
IMPINGER SYSTEM
COMBINE AND MEASURE TOTAL VOLUME FOR SINGLE ANALYSIS
IMPINGER 3
TRANSFER TO NALGENE CONTAINER
RINSE WITH 1:1 ISOPROPYL ALCOHOL (IPA)/ DISTILLED WATER AND ADD
IMPINGER 4 SILICA GEL
DISCARD

Figure 13. Sample handling and transfer of impinger contents for those SASS runs made for chemical analysis (20).

Wood and Combustion Residue

Samples of the test wood were obtained by Auburn University prior to testing. MRC submitted these samples to Industrial Testing Laboratories, St. Louis, Missouri, for proximate and ultimate analysis. Combustion residues ("ash") were quantitatively removed from the combustion unit after being allowed to burn out and cool overnight. The mass was weighed and saved in polyethylene jars for bioassay analysis.

Flue Gas Velocity Measurement

Because flue gas velocities were generally below 200 m/min and often below 100 m/min, it was necessary to employ a velocity measuring system more sensitive to low velocities than the "S" type pitot tube and conventional micromanometer.

The flue-gas velocity measurement device chosen for this study was a Model 308R fluidic flowmeter (FluiDynamic Devices Limited, Canada). The working element of the unit is a free, unbounded jet. The jet, composed of a supply fluid compatible with the gas to be measured, issues from a nozzle and is directed toward two total head receiver ports. At zero cross flow, the pressure cone produced by the jet covers both receiver ports equally, establishing a zero pressure differential. When the product to be measured flows across and entrains with the jet, the jet deflects. This places unequal pressures on the receiver ports, establishing a pressure differential between them. The differential varies directly with the gas flow and is measured with a suitable manometer. This device was coupled to a strip chart recorder for permanent recording of low rate changes. Velocity measurement and recording was excellent initially; however, after about an hour of operation, the readings became erratic. The problem appeared to be a buildup of creosote or soot on the edges of the nozzles which resulted in a change of calibration. Recalibration of the unit proved to be only a temporary solution since either more buildup occurred or previous buildup broke off. Cleaning the probe also provided only a temporary solution, and the device was finally taken out of service.

Velocities for this program were finally determined by employing an "S" type pitot tube and a Meriam micromanometer (Model 34FB2, serial No. U43843) with a range of 0-37.36 mm Hg. This manometer uses a scale of much greater expansion than the typical field micromanometer and employs a vernier adjustment to obtain a velocity reading in inches of water. The manometer was extremely sensitive to velocity changes at low flow rates and could be accurately read down to 1.87×10^{-4} mm Hg.

Fuel Burning Rate Determination

The wood burning stoves tested and the associated flue pipe were mounted on an electronic scale which provided digital readout of mass. Readings were taken prior to and immediately after charging wood to determine the weight of a wood charge. Readings were also taken at the start-up and shut-down of various sampling trains to facilitate emission factor determination. Auburn University also took weight readings at 5-min intervals during efficiency testing.

As a precaution against sampling probes affecting weight readings during thermal expansion and contraction of the stack, the sampling trains were suspended by cables and balanced. In this way, any upward or downward movement of the stack caused the train to pivot rather than exert a force against the stack and influence weight readings. Weight readings taken with and without the trains in place showed no more than 0.05 kg influence on the weight determination.

Because of the size and mass of the fireplace, the electronic scales could not be utilized. However, the 5-min weight readings during testing of the wood burning stoves showed that the wood mass decrease during combustion was nearly linear. Therefore, by weighing all wood charges to the fireplace and observing the length of burn of several wood charges, the mass burned during testing could be determined from the length of the test.

LABORATORY SEPARATION AND ANALYSIS PROCEDURES

At the completion of each two-week interval of field sampling, individual bottles containing the contents and clean-up solutions of the various sampling trains were delivered to MRC's Dayton Laboratory. The laboratory effort included separation schemes and analytical procedures in order to characterize the source emissions. The following section presents the details of these procedures.

Particulates and Condensable Organics

Samples for particulate analysis from the Method 5 train (front half washings and filter) were analyzed according to the Method 5 procedure as specified in the Federal Register (11). The back-half portion of the train (impinger contents and back-up filter) was used to determine the mass of condensable organic material. The back-up filter was desiccated overnight to a constant weight. The impinger solutions were evaporated to dryness at about 95°C and weighed to determine the residue mass. The combination of residue mass and filter weight gain is reported as condensable organic material.

Particulate emissions were also determined from the front-half mass of the POM train. This portion of the POM train is identical to the Method 5 train and the particulates were determined accordingly. After mass determination the particulate samples were submitted for POM and organic analysis.

In addition to the above analyses, particulate samples were submitted to industrial Testing Laboratories (St. Louis, Missouri) for analysis of carbon, hydrogen, and nitrogen using a Perkin Elmer Model 240 elemental analyzer.

Samples recovered from the front half of the SASS train were also used to semiquantitatively measure particulate emissions. All front-half washes were evaporated to dryness. These samples, along with the cyclone catches and filters, were desiccated overnight to a constant weight. The resulting mass collected was used to determine particulate emissions by size fraction.

Sulfur Oxides and Nitrogen Oxides

Method 6 samples for SO_2 determination were analyzed using the Federal Register procedure (14). Samples collected by Method 7 for NO_x determination were partially worked up at the test site by recording ambient temperature, barometric pressure, and internal flask pressure and adjusting the solution pH for NO_x fixation. Final analysis for NO_x was conducted at MRC's Dayton Laboratory. All procedures followed those given in the Federal Register (15).

Formaldehyde

Aldehydes were collected in an impinger containing a 10% sodium bisulfite solution. Concentrations of formaldehyde greater than or equal to 0.02 ppm were determined using Tentative Method 110 as proposed by the Interscience Committee (17). In this procedure, a mixture of chromotropic acid and sulfuric acid is used as the reagent. The transmittance is read at 580 nm. Saturated aldehydes gives less than 0.01% positive interference, and the unsaturated aldehyde acrolein results in a few percent positive interference. Ethanol and higher molecular weight alcohols and olefins in mixtures with formaldehydes are negative interferences. However, concentrations of alcohols in air are usually much lower than formaldehyde concentrations and, therefore, are not a serious interference.

This was not the original method attempted but was resorted to after three other methods were tried and failed to show color development for 90 ppm formaldehyde (HCHO) in 10% $NaHSO_3$. The methods attempted were 1) modified Shiffs with para-rosaniline and HCl (21), 2) modified Shiffs with para-rosaniline and H_2SO_4 (21), and 3) MBTH (22). One reviewer of this report noted that the analysis method chosen was not generally considered reliable, and that the presence of polar organics would tend to reduce the reliability even more.

Other Aldehydes

C_2 to C_5 aldehydes were collected in impingers containing a 10% $NaHSO_4$ solution. The analysis method is patterned after Tentative Method 110 as proposed by the Interscience Committee and can be found in Reference 18.

The aldehydes were measured using GC/FID. The GC column was stainless steel (1.7 m x 3 mm) packed with uncondenonylphthalate on firebrick followed by a 4 m x 3 mm stainless steel column packed with 15% by weight Carbowax 20M on Chromasorb, 60 to 80 mesh. Retention times for the various species, under the conditions given in Reference 18 are presented in Table 7.

TABLE 7. RETENTION TIMES FOR ALDEHYDES

Compound	Retention time, min
Acetaldehyde	3.92
Propionaldehyde	5.11
Isobutylaldehyde	5.91
n-Butyraldehyde	7.77
Crotonaldehyde	unknown

POM Train Sample Pretreatment

Samples collected from the Modified EPA Method 5 sample train were received from the field in the following forms:

- Particulate samples from the probe washes
- Glass fiber filter
- XAD-cartridge
- Contents of water impingers and cooler trap
- Methylene chloride rinses

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(21) Lyles, G. R., F. B. Dowling, and V. J. Blanchard. Quantitative Determination of Formaldehyde in Parts Per Hundred Million Concentration Level. Journal of the Air Pollution Control Association, 15(3):106-108, 1965.

(22) Tentative Method of Analysis for Formaldehyde Content of the Atmosphere (MBTH-Colorimetric Method - Applications to Other Aldehydes). Health Laboratory Science, 7(3):173-178, 1970.

The XAD-2 trap, probe washings, and the filter were subjected to Soxhlet extraction with methylene chloride (CH_2Cl_2) for 24 hr. The CH_2Cl_2 was then reduced to a volume of approximately 5 mL by means of rotary evaporation at a pressure greater than 10 mm Hg and a water bath temperature of less than 45°C. Following volume reduction, the sample underwent a solvent exchange with hexane and was reduced to 10 mL by Rotovap. It was observed that a significant portion of the material that was soluble in methylene chloride would not go into hexane. This material was recovered and resolubilized in methylene chloride. A solid precipitate also formed during solvent exchange but was not analyzed. The hexane-soluble fraction was separated into eight fractions on a silica gel column. An aliquot of each fraction was then reduced in volume using a Kuderna-Danish evaporator and transferred to a tare-weighed micro-weighing pan, and the remaining solvent evaporated in air. Each dried fraction was weighed and then redissolved in a minimum quanity of methylene chloride. The eight fractions are shown in Figure 14. All eight fractions of one run were analyzed on GC/MS. It was found that the most cost effective approach for analysis was to analyze fraction 1 separately and combine fractions 2, 3, and 4 as well as fractions 5, 6, and 7. Fraction 8 was observed to contain little or no detectable organic compounds and was therefore dropped from the scheme.

The water impinger contents of one run underwent an acid, base, ether extraction. It was determined by TOC analysis of the remaining aqueous phase that only 30% of the organic carbon was extracted and the remainder was contained in the aqueous phase. The water impinger contents of the remaining runs were evaporated to dryness under vacuum, and the residue was recovered in methanol. Ultimately, the following samples were submitted for GC/MS analysis:

- Hexane-soluble fraction 1
- Hexane-soluble fractions 2, 3, 4
- Hexane-insoluble fraction in methylene chloride
- Impinger water residue in methanol

Figure 14 presents the analysis flow diagram for the POM train samples.

The hexane-soluble fractions were analyzed for organic species on a Hewlett-Packard GC/MS system (Model 5982-A or HP5983-A) using the following general conditions: 6.4 m x 1.8 m glass column packed with 3% Dexsil 400 on Chromosorb W-HP, 60°C, 2 min/16°C per minute/280°C (on HP5982-A) or 300°C (on HP5983-A), helium flow: 30 mL/min. In addition, POM's were specifically sought for using SIM (Selected Ion Monitoring) programming.

The hexane-insoluble samples were found to be largely nonchromatographable; however, the chromatographable portion contained a significant mass of organic compounds. This material was

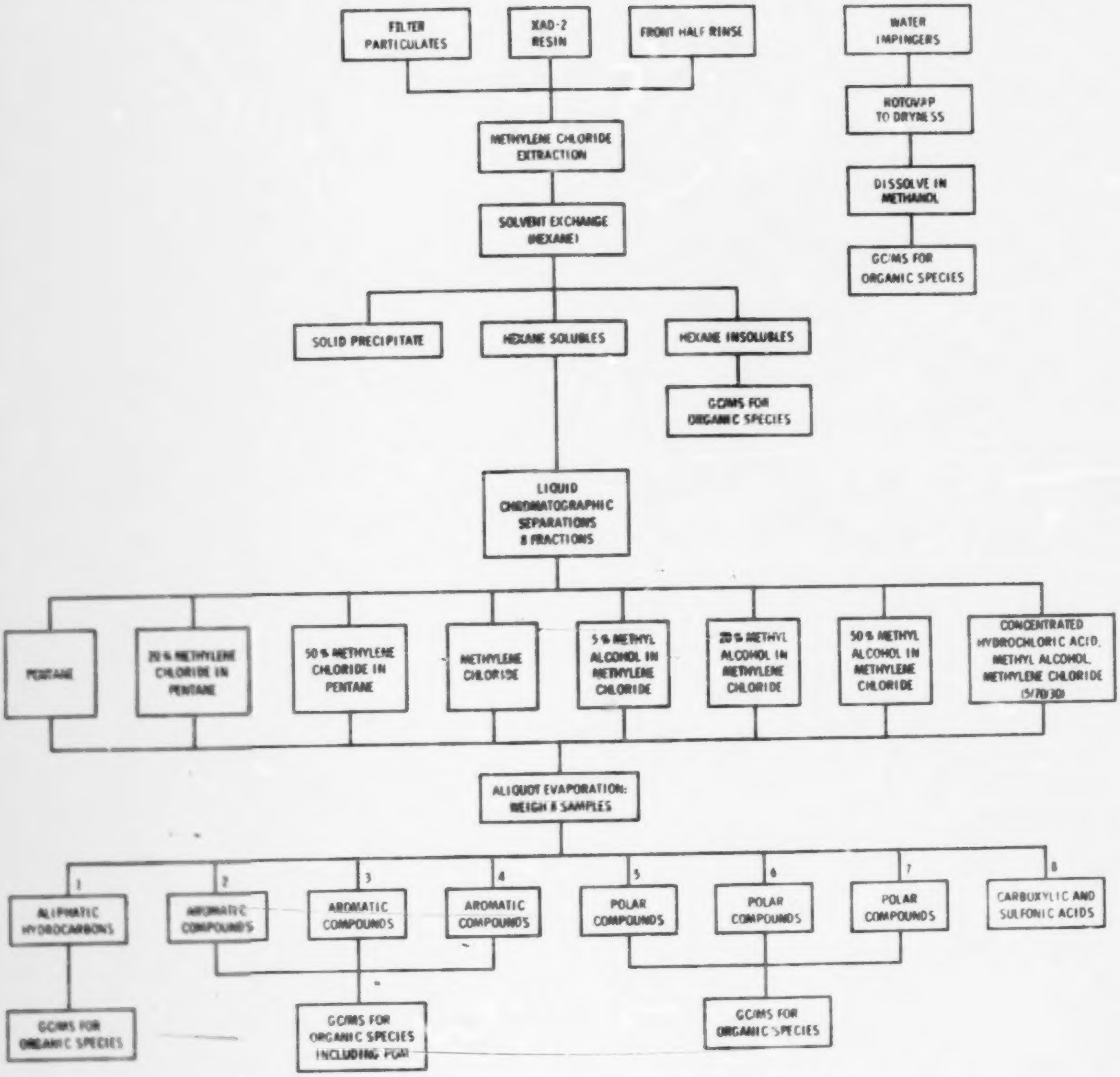
FILTER PARTICULATES
XAD-2 RESIN
FRONT HALF RINSE
WATER IMPINGERS
ROTOVAP TO DRYNESS
DISSOLVE IN METHANOL
GC/MS FOR ORGANIC SPECIES
METHYLENE CHLORIDE EXTRACTION
SOLVENT EXCHANGE (HEXANE)
SOLID PRECIPITATE
HEXANE SOLUBLES
HEXANE INSOLUBLES
GC/MS FOR ORGANIC SPECIES
LIQUID CHROMATOGRAPHIC SEPARATIONS 8 FRACTIONS
PENTANE
20% METHYLENE CHLORIDE IN PENTANE
50% METHYLENE CHLORIDE IN PENTANE
METHYLENE CHLORIDE
5% METHYL ALCOHOL IN METHYLENE CHLORIDE
20% METHYL ALCOHOL IN METHYLENE CHLORIDE
50% METHYL ALCOHOL IN METHYLENE CHLORIDE
CONCENTRATED HYDROCHLORIC ACID, METHYL ALCOHOL, METHYLENE CHLORIDE (5/70/30)
ALIQUOT EVAPORATION: WEIGH 8 SAMPLES
1
ALIPHATIC HYDROCARBONS
2
AROMATIC COMPOUNDS
3
AROMATIC COMPOUNDS
4
AROMATIC COMPOUNDS
5
POLAR COMPOUNDS
6
POLAR COMPOUNDS
7
POLAR COMPOUNDS
8
CARBOXYLIC AND SULFONIC ACIDS
GC/MS FOR ORGANIC SPECIES
GC/MS FOR ORGANIC SPECIES INCLUDING POM
GC/MS FOR ORGANIC SPECIES

Figure 14. POM train sample analysis scheme for organic species and POM compounds.

examined by GC/MS under the same conditions as the hexane-soluble fractions. A variety of species, including POM's, were detected and quantitated. A DIP (Direct Injection Probe) run was also made on one of these samples and revealed, in addition to the species already identified by GC/MS, a continuous stream of ions, many above 301 (the molecular ion of dibenzopyrene). This suggests a variety of high molecular weight fused-ring aromatics (e.g., POM's, M.W. greater than 302). As an example, a POM of molecular weight 326 could be isolated. Here, the "bake-off" temperature of the DIP is the limiting factor in the amount of material generating this pattern.

Likewise, a GC run of a methanol solution of the aqueous residue revealed no detectable species (with some programming). A DIP run on this sample, yielded only ions associated with organic (aliphatic) acids. No molecular ions were generated to provide a molecular weight range; however, the broadness of the thermogram suggests a rather high molecular weight range (probably greater than 284 - stearic acid).

Direct injection of the water from the impingers into the GC/MS provided no information; no organic species were detectable in the sample at the level provided (approximately 5 to 50 μg/mL for general response range).

The method used for POM analysis employed a peak-area quantitation technique with computer-reconstructed chromatograms from the GC/MS. All data were collected in the electron impact (EI) mode because of the abundance of available EI-mass spectra.

Gas chromatographic separation was achieved using a 6-ft Dexsil 400 glass column with temperature programming from 160°C for 2 min, rising to 280°C at 8°C/min, and becoming isothermal at 280°C. The carrier gas was helium at a flow rate of 30 mL/min.

The mass spectrometer, operating in the EI mode, was programmed to scan the 35-350 atomic mass unit (amu) range as the POM components eluted from the gas chromatograph. The data system reconstructed the chromatogram using the total ion mode. POM's were located by their molecular mass ions which were displayed using the selected ion mode (SIM). Their identity was confirmed by examination of their mass spectra and retention times. Samples and standards were run in SIM for quantitation.

Standard responses were determined for each POM of interest using varying concentrations of standards in methylene chloride, and calculating average mass ion peak area per unit concentration. Sample peaks were compared with standard response factors that were obtained under the same conditions of attenuation, injection volume (2 μL), and tuning condition.

SASS Train Work-Up and Analysis

The Source Assessment Sampling System (SASS) employed in this program allowed the collection of many components of an emission source in a single test. However, the separation and analysis schemes were complex because of the many components. Once separation was accomplished, the analytical method for any particular component class or compound (e.g., trace metals or POM) was identical regardless of the source of the sample. As a result, a major portion of the analytical effort concerned the separation of components prior to analysis.

At the completion of a sample run, the samples collected by this system included the contents of the three cyclones, the filter, the combined probe and cyclone washes, the XAD-2 resin trap, the XAD-2 trap condensate, the XAD-2 washes, and the combined impinger collection and washes.

In order to determine a mass loading, the materials collected from the cyclones and filter were individually weighed. The probe and cyclone wash was evaporated to dryness and weighed, and this plus the cyclone-collected material and the filter catch provided a "front half" mass for the calculation of the particulate emission rate. All of the solid materials were then combined and extracted with methylene chloride for 24 hr in a Soxhlet extractor in order to extract organic materials.

At this point, five samples existed:

- extracted solids (filter, cyclones, XAD-2 resin)
- solid extract containing organics
- resin trap washes
- resin trap condensate
- impinger contents

Chemical Analysis--

Two SASS train runs were made for chemical analysis: one for organic analysis only and one for organic and trace element analysis. The trains differed only in impinger solutions where the train for organic analysis employed only distilled, deionized water and that for trace element analysis employed the reagents shown earlier in Table 6. The separation and analysis scheme for organic compounds closely paralled that used for the POM train shown in Figure 14. In this case, the resin module condensate was combined with the impinger solutions, prior to evaporation.

Prior to extraction, a 5-g portion of XAD-2 resin was saved for trace element analysis. The remaining solids were also submitted for trace element analyses as were the resin trap condensate and reagent impinger solutions. Atomic absorption was used to determine arsenic, mercury, and selenium (23). Inductively coupled argon plasma emission spectroscopy was used to quantify aluminum antimony, barium, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, phosphorus, silicon, silver, sodium, strontium, tin, titanium, vanadium, and zinc. The AtomComp with ICAP forms an analytical system for simultaneous multielement determinations of trace metals at the sub-ppm level in solutions. The basis of the method is atomic emission promoted by coupling the sample, nebulized to form an aerosol, with high temperature argon plasma produced by passage of argon through a powerful radio-frequency field (24).

All of the solid samples were digested before analysis using the acid digestion Parr bomb technique originally developed by Bernas and modified by Hartstein for trace metal analyses of coal dust by atomic absorption (25, 26). This method employs the Parr 4145 Teflon-lined bomb and involves digestion of powdered samples in ULTRAR brand (69% to 71%) redistilled nitric acid at 150°C. The accuracy of this method for coal dust analysis, reported for 10 metals, ranged from 94% for beryllium to 106% for nickel using 10-mg samples. Sample solutions produced by acid digestion were diluted with distilled deionized water to reduce acid concentrations to approximately 2% and submitted for analysis.

Aqueous impinger solutions from the SASS train were analyzed for the volatile elements which could not be 100% collected by the filter, i.e., mercury, arsenic, selenium, and antimony.

Bioassay--

Twelve SASS runs were made to provide samples for bioassay: one for each test condition. Bioassay was conducted by Litton Bionetics for the EPA under separate contract. Each SASS run resulted in two samples for bioassay. The first consisted of the methylene chloride extract of all front-half material (cyclone and filter catches and wash residues). It was determined that bioassay of the individual components would be meaningless because most of the front-half catch was recovered in the washings, indicating the train did not effectively size the particles. Because of the organic nature of the material collected, it was desired to only test the methylene chloride soluble fraction.

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(23) Metals by Atomic Absorption Spectrophotometry. In: Standards Methods for the Examination of Water and Wastewater, 14th Edition. American Public Health Association, Washington, D.C., 1976. pp. 143-270.

(24) Jarrell-Ash Plasma AtomComp for the Simultaneous Determination of Trace Metals in Solutions (manufacturer's brochure). Catalog 90-975, Jarrell-Ash Company, Waltham, Massachusetts. 5 pp.

(25) Bernas, B. A New Method for Decomposition and Comprehensive Analysis of Silicates by Atomic Absorption Spectrometry. Analytical Chemistry, 40(11):1682-1686, 1968.

(26) Hartstein, A. M., R. W. Freedman, and D. W. Platter. Novel Wet-Digestion Procedure for Trace-Metal Analysis of Coal by Atomic Absorption. Analytical Chemistry, 45(3):611-614, 1973.

The second sample submitted consisted of the methylene chloride extract of the XAD-2 resin and the methylene chloride rinse of the XAD-2 module. The methylene chloride solvent was exchanged for dimethyl sulfoxide (DMSO) prior to submitting the samples to Litton. Twelve samples of each were submitted for Salmonella/microsome mutagenesis assay (Ames Test) and clonal toxicity (CHO) assay.

Combustion Residue

Combustion residue samples (ash) were collected from each test condition, and 8 were submitted to Litton for bioassay. Table 8 presents the bioassays performed on each of these samples.

TABLE 8. COMBUSTION RESIDUE SAMPLE TEST CONDITIONS AND BIOASSAYS PERFORMED

Sample code	Test condition	Bioassay performed
A-1	Fireplace - seasoned oak	Ames and RAM[a]
A-2	Fireplace - green oak	Aquatic[b]
A-3	Fireplace - seasoned pine	Whole animal[c]
B-2	Baffled stove - green oak	Ames and RAM[a]
B-3	Baffled stove - seasoned pine	Ames and RAM[a]
C-2	Nonbaffled stove - green oak	Whole animal[c]
C-3	Nonbaffled stove - seasoned pine	Aquatic[b]
C-4	Nonbaffled stove - green pine	Ames and RAM[a]

[a] Cytotoxicity.

[b] Aquatic ecological effects (acute static bioassay - *Daphnia*).

[c] Acute *in-vivo* in rodents.

SECTION 4

RESULTS

Test results for the sampling and analysis of emissions from residential wood-burning stoves and fireplaces are discussed in this section. Each emission species measured is addressed separately and correlated to test parameters where possible. Overall conclusions and potential implications of the test results are then considered. Because a wide range of combustor designs, operating conditions, and fuel types could not be studied in detail in this program, caution should be exercised in extrapolating these results to other combustion equipment, wood types, or test conditions.

EMISSIONS SUMMARY

Emission rates[a], expressed as grams of pollutant emitted per kilogram of wood burned, for the test conditions used in this program are summarized in Table 9 for criteria pollutants and POM emissions. These data were obtained by employing standard EPA methods except in the case of POM's which were measured with a modified EPA method. Other less quantitative or more specific emission data are presented later in this section. Additional test parameters which were measured to characterize combustion conditions are presented in Table 10.

Particulate Emissions

Particulate emissions were determined by measuring the mass of material collected by the front half of the SASS train, the POM train and the EPA Method 5 train. The results, reported in Table 11, shows that there is no significant variation between the emissions from the fireplace and the wood stoves. A statistical analysis supports this conclusion (see Appendix B). The particulate emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, vary from 0.6 g/kg to 6.0 g/kg wood burned. This variation can be attributed to the variable nature of the combustion process.

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[a] Emission rates are expressed as grams of pollutant emitted per kilogram of wood burned (g/k) throughout this report.

TABLE 9. SUMMARY OF EMISSION RESULTS FOR CRITERIA POLLUTANTS AND POM's FROM WOOD-FIRED RESIDENTIAL COMBUSTION EQUIPMENT

Wood burning device	Wood type	Emission rate, g/kg[a] (μg/J)[b]						
		Particulate matter[a]	Condensable organics[b]	Volatile hydrocarbons[c]	NO_x[d]	SO_x[e]	CO[f]	POM[g]
Fireplace	Seasoned oak	2.3 (0.13)	6.3 (0.35)	19 (1.1)	2.4 (0.13)		30 (1.7)	0.025 (0.0014)
Fireplace	Green oak	2.5 (0.19)	5.4 (0.40)		1.9 (0.14)		22 (1.6)	
Fireplace	Seasoned pine	1.8 (0.10)	5.9 (0.32)		1.4 (0.08)		21 (1.2)	
Fireplace	Green pine	2.9 (0.21)	9.1 (0.67)		1.7 (0.13)		15 (1.1)	0.036 (0.0026)
Baffled stove	Seasoned oak	3.0 (0.17)	4.0 (0.22)		0.4 (0.02)		110 (6.2)	0.21 (0.012)
Baffled stove	Green oak	2.5 (0.19)	3.8 (0.28)		0.7 (0.05)		120 (9.0)	
Baffled stove	Seasoned pine	3.9 (0.21)	4.1 (0.23)	2.8 (0.15)	0.5 (0.03)		270 (15)	0.37 (0.020)
Baffled stove	Green pine	7.0 (0.51)	12 (0.88)		0.8 (0.06)		220 (16)	
Nonbaffled stove	Seasoned oak	2.5 (0.14)	6.0 (0.34)		0.4 (0.02)	0.16 (0.009)	370 (21)	0.19 (0.011)
Nonbaffled stove	Green oak	1.8 (0.13)	3.3 (0.25)	0.3 (0.02)	0.5 (0.04)		91 (6.8)	
Nonbaffled stove	Seasoned pine	2.0 (0.11)	5.6 (0.31)		0.2 (0.01)	0.24 (0.013)	150 (8.2)	
Nonbaffled stove	Green pine	6.3 (0.46)	10 (0.74)	3.0 (0.22)	0.4 (0.03)		97 (7.1)	0.32 (0.024)

Note: Blanks indicate no data were obtained.

[a] Front half of EPA Method 5 and POM train. Averaged when two values are available.

[b] Back half of EPA Method 5. Averaged when two values available.

[c] GC/PID.

[d] EPA Method 7. Average of 6 grab samples.

[e] EPA Method 6.

[f] EPA Method 3 (Orsat) for stoves; average of 10 samples. Dräger tube for fireplace; 15-30 minute composite.

[g] POM train (EPA Method 5 modified with XAD resin trap).

TABLE 10. SUMMARY OF TEST CONDITIONS DURING TESTING OF WOOD-FIRED RESIDENTIAL COMBUSTION EQUIPMENT

Wood burning device	Wood type	Wood burning rate,[a] kg/min	Average stack gas conditions						
			Temperature,[b] °C	Velocity,[b] m/min	Flow rate,[b] Nm^3/min	H_2O,[b] %	CO_2,[c] %	O_2,[c] %	CO,[c] %
Fireplace	Seasoned oak	0.18	152	308	6.5	3.8	0.5	21	0.07
Fireplace	Green oak	0.17	207	347	6.4	4.2	0.5	21	0.05
Fireplace	Seasoned pine	0.19	236	367	6.5	3.8	0.5	21	0.04
Fireplace	Green pine	0.16	207	332	6.5	0.5	0.5	21	0.04
Baffled stove	Seasoned oak	0.14	307	184	1.5	13	7.7	13	0.7
Baffled stove	Green oak	0.11	300	117	0.9	11	9.2	11	1.1
Baffled stove	Seasoned pine	0.12	378	146	1.0	15	14	4.4	2.8
Baffled stove	Green pine	0.10	247	213	2.0	11	9.4	11	0.9
Nonbaffled stove	Seasoned oak	0.13	384	128	0.9	11	14	5.5	2.8
Nonbaffled stove	Green oak	0.11	240	89	0.9	4	11	9.3	1.0
Nonbaffled stove	Seasoned pine	0.12	304	109	0.9	11	11	8.4	1.6
Nonbaffled stove	Green pine	0.13	305	111	0.8	15	9.9	10	1.5

[a] Average burning rate during EPA Method 5, POM, and SASS train operation.

[b] Determined from average EPA Method 5 data.

[c] Determined by Orsat and Dräger tube.

TABLE 11. PARTICULATE EMISSIONS FROM WOOD BURNING FIREPLACES AND STOVES (g/kg)

Combustion equipment	Sampling method	Wood type			
		Seasoned oak	Green oak	Seasoned pine	Green pine
Fireplace	EPA 5	1.9	2.5	1.8	2.8
	EPA 5 (modified)[a]	2.8			3.1
	SASS train[a]	1.6	1.0	2.0	1.5
	SASS train	2.9			
Baffled stove	EPA 5	1.5	4.4	3.1	6.0
	EPA 5		0.6		8.1
	EPA 5 (modified)	4.5		4.7	
	SASS train	0.6	2.7	4.8	0.6
Nonbaffled stove	EPA 5	1.9	1.8	2.0	5.1
	EPA 5 (modified)	3.1			7.6
	SASS train	2.2	2.3	3.2	4.4
	SASS train				3.8

[a] Discussed in Section 3.

Factors such as the addition of fresh wood charges, fuel bed configuration, size of fuel charge, etc., all have some effect on emissions generated from fireplaces and wood burning stoves.

Because the POM train is operated as an EPA Method 5 train and both front-half components are identical, the particulate emission results from both trains can be considered of identical quality. In some cases there are large differences between replicate tests; however, the average emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, are consistent with other tests. This supports the contention of the natural variability of the process and demonstrates the need for replicate testing.

The SASS train particulate emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, were determined from particulates collected in a series of cyclones and a filter for the purpose of estimating the size distribution of particulates. Table 12 presents the distribution of particulates collected by the SASS train as percent of the total mass collected. The front-half washings, considered to represent particles greater than 10 μm in diameter, represented 33% to 62% of the particulates, while the filter (less than 1 μm diameter particles) collected 34% to 63% of the particles. The remainder of the particles (2% or less) were trapped in the cyclones. With such an odd distribution of particles, it can be inferred that true particle sizing did not occur. Field observations indicated that the material collected in the front half of the train included large quantities of condensed resinous material which adhered to component surfaces and was difficult to remove.

TABLE 12. PARTICULATE LOADING OF SASS TRAIN COMPOSITION EXPRESSED AS PERCENT OF TOTAL PARTICULATE CATCH[a]

Combustion equipment	Wood type	Particulate loading, % of total Front half wash	Large cyclone	Middle cyclone	Small cyclone	Filter
Fireplace	Seasoned oak	64	2	1	2	32
	Green oak	23	1	0	1	75
	Seasoned pine	69	2	3	2	24
	Green pine	76	2	0	0	22
Baffled stove	Seasoned oak	7	2	3	1	88
	Green oak	53	1	2	0	44
	Seasoned pine	61	2	2	1	35
	Green pine	11	1	2	2	84
Nonbaffled stove	Seasoned oak	51	3	4	4	38
	Green oak	64	1	0	1	34
	Seasoned pine	67	1	0	1	31
	Green pine	66	1	1	1	32

[a] Some values do not add up to 100% because of round-off error.

An analysis of the filter catch was performed to determine the composition of the particulate emissions. Table 13 presents the carbon, hydrogen, and nitrogen content of particulates collected on EPA Method 5 filters and POM train filters after methylene chloride extraction.

TABLE 13. CARBON, HYDROGEN, AND NITROGEN CONTENT OF PARTICULATE EMISSIONS FROM WOOD BURNING FIREPLACES AND STOVES

Test condition code	Sample identification	Composition of particulate, % Carbon	Hydrogen	Nitrogen
A-4	EPA-5 front half filter catch	50.7	1.9	0.3
A-4	POM train filter catch after extraction	64.6	2.1	0.2
B-1	EPA-5 front half filter catch	50.8	1.7	0.6
B-1	POM train filter catch after extraction	38.6	2.4	0.4
B-3	EPA-5 front half filter catch	79.0	2.1	0.3
B-3	POM train filter catch after extraction	76.5	2.1	0.3

The composition of the particulates remained essentially unchanged after methylene chloride extraction indicating 1) that no organic material was extractable from the particulates or 2) that what was extracted had a carbon content identical to that of the nonextractable fraction.

About 40% of the particulate matter was unaccounted for by carbon, hydrogen, and nitrogen analysis. Inorganic components should be negligible because of the low fuel ash content (less than 1%). Therefore, based on the fuel analysis (Table 13), it would be reasonable to conclude that the remaining portion is oxygen. The analysis of the particulates then compares closely with the fuel analysis on a dry basis with about 60% carbon in the particulates and about 50% carbon in the wood. The slight difference can be attributed to some loss of hydrogen and oxygen during combustion. The actual chemical structure of the particulates, however, in no way resembles that of the wood. The particulates were a dark brown or black sooty, carbon-black-like material which exhibited some resinous qualities.

Trace Elements

This is the first study undertaken to characterize the magnitude of trace element emissions from wood-fired residential heating equipment. Table 14 presents emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, for 29 elements identified in the analysis of samples taken while burning green pine in the nonbaffled stove. The emission rates determined during this study range from 1.4×10^{-7} g/kg to 4.2×10^{-2} g/kg. The highest values measured (1.8×10^{-2} g/kg for silver and 4.2×10^{-2} g/kg for zinc) are believed to be in error. Silver analysis with the ICAP technique tends to give high readings at low concentrations, and many of the elements (including silver) were near their detection limits in this analysis. The high reading for zinc may result from volatilization of zinc from the galvanized stack.

The ash composition of wood can range from 0.2% to 2.2%, with calcium, potassium, phosphorus, sodium, and magnesium being the predominant elements (10, 27-30). These same elements have relatively high emission rates in Table 14 (on the order of 10^{-3} g/kg), but the absolute value of the emission rates is two or three orders of magnitude lower than their typical concentration

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(27) Schorger, A. W. Chemistry of Cellulose and Wood. McGraw-Hill Book Company, New York, New York, 1926. p. 51.

(28) Young, H. E. Preliminary Estimates of Bark Percentages and Chemical Elements in Complete Trees of Eight Species in Maine. Forest Products Journal, 21(5):56-59, 1971.

(29) Mingle, J. G., and R. W. Boubel. Proximate Fuel Analysis of Some Western Wood and Bark. Wood Science, 1(1):29-36, 1968.

(30) Fernandez, J. H. Why Not Burn Wood? Chemical Engineering, 84(11):159-164, 1977.

TABLE 14. ELEMENTAL EMISSIONS OBTAINED FROM THE NONBAFFLED WOODBURNING STOVE

Emission species	Emission rate, g/kg	Emission species	Emission rate, g/kg
Aluminum	1.5×10^{-3}	Mercury	1.3×10^{-4}
Antimony	2.3×10^{-5}	Molybdenum	2.3×10^{-4}
Arsenic	1.3×10^{-4}	Nickel	1.7×10^{-3}
Barium	2.0×10^{-4}	Phosphorus	7.0×10^{-5}
Beryllium	1.4×10^{-7}	Selenium	1.3×10^{-4}
Boron	7.3×10^{-4}	Silicon	2.7×10^{-3}
Cadmium	3.6×10^{-5}	Silver	1.8×10^{-2}
Calcium	4.7×10^{-3}	Sodium	3.0×10^{-3}
Chromium	9.0×10^{-4}	Strontium	1.1×10^{-5}
Cobalt	6.0×10^{-5}	Tin	3.8×10^{-5}
Copper	1.7×10^{-4}	Titanium	1.0×10^{-5}
Iron	3.1×10^{-3}	Vanadium	1.5×10^{-5}
Lead	4.8×10^{-4}	Yttrium	9.3×10^{-5}
Magnesium	2.9×10^{-4}	Zinc	4.2×10^{-2}
Manganese	1.9×10^{-4}		

in wood. Thus only a small fraction of the trace element content of wood is emitted to the atmosphere.

Condensable Organics

Condensable organic emissions were determined by measuring the mass of material collected in the back of the EPA Method 5 particulate train. The back half of this train consisted of impingers containing distilled water and a back-up filter which collected most of the materials passing through the front-half filter. The impinger solutions ranged from yellow to light brown in color, while the back-up filter catches were consistently yellow. Connecting glassware was dotted with brown resinous material which proved difficult to recover. This material, if emitted, would condense in the atmosphere and could be considered as part of the particulate emissions; however, for this study, it is reported separately.

Emission rates for condensable organic material, expressed as grams of pollutant emitted per kilogram of wood burned, are presented in Table 15 and range from an average of 2.2 g/kg to 14 g/kg. A statistical analysis indicates that condensable organic emissions are over two times higher when burning green pine than when burning the other three wood types tested (see Appendix B). The combustion equipment type had no significant effect on condensable organic emission rates. The condensable organics accounted for 54% to 76% of the total mass collected by the EPA Method 5 train (see Table 11); 12% to 39% of the back-half mass was collected on the back-up filter.

TABLE 15. CONDENSABLE ORGANIC MATERIAL EMISSIONS[a]
(g/kg)

Combustion equipment	Type of wood Seasoned oak	 Green oak	 Seasoned pine	 Green pine
Fireplace	6.3	5.4	5.9	9.1
Baffled stove		5.4		14.3
	4.0	2.2	4.1	9.4
Nonbaffled stove	6.0	3.3	5.6	10.1

[a] As determined from back half of EPA Method 5 train.

Nitrogen Oxides

A total of 72 samples were collected for the analysis of NO_x emissions from wood-burning stoves and fireplaces. Six samples were taken randomly throughout several burning cycles of each test condition so that the resulting emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, would be representative of the wood burning process. The resulting NO_x emission rates are presented in Table 16.

TABLE 16. NITROGEN OXIDE EMISSIONS
(g/kg)

Combustion equipment	Type of wood Seasoned oak	 Green oak	 Seasoned pine	 Green pine
Fireplace	2.3	3.5	0.8	1.9
	2.5	3.3	1.0	1.7
	2.7	0.2	2.2	1.8
	2.6	2.1	1.3	1.8
	2.0	2.0	1.6	1.7
	2.1	0.2	1.6	1.3
	2.4[a]	1.9[a]	1.4[a]	1.7[a]
Baffled stove	0.7	0.9	0.4	0.3
	0.3	0.3	0.3	0.8
	0.3	0.8	0.8	0.6
	0.6	1.2	0.1	1.1
	0.3	0.7	0.7	0.9
	0.2	0.3	0.6	0.9
	0.4[a]	0.7[a]	0.5[a]	0.9[a]
Nonbaffled stove	0.6	0.5	0.2	0.5
	0.2	0.7	0.1	0.2
	0.4	0.4	0.2	0.5
	0.2	0.8	0.2	0.7
	0.7	0.4	0.2	0.3
	0.5	0.4	0.3	0.2
	0.4[a]	0.5[a]	0.2[a]	0.4[a]

[a] Average.

The consistency of the replicate samples indicates that the stage of the burning cycle had negligible effect on NO_x emissions. This is verified statistically in Appendix B.

A statistical analysis was performed to determine the effect of combustion equipment and wood type on NO_x emission rates (Appendix B). The results support the observed difference in NO_x emissions between the fireplace and stoves. No significant difference exists between NO_x emissions from the wood types tested. However, the statistical analysis revealed a large error term, indicating an unknown variable was influencing the NO_x emission rates.

Based on average emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, the fireplace emits about four times as much NO_x as the stoves per unit of wood burned. Increased NO_x emissions are generally associated with higher combustion temperatures. This is consistent with the lower CO and POM emissions (products of incomplete combustion) associated with the fireplace since higher combustion temperatures are indicative of greater combustion efficiency. A possible explanation for this may be the higher combustion air velocities associated with the fireplace which cause more rapid burning and thus higher temperatures. The burning rate of the fireplace was about 40% greater than that of the stoves.

Carbon Monoxide

Carbon monoxide (CO) is a product of incomplete combustion and is a major pollutant emitted from wood-burning fireplaces and stoves. Table 17 presents the CO emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, determined in this program; they range from 11 g/kg to 40 g/kg for the fireplace and from 83 g/kg to 370 g/kg for the stoves.

TABLE 17. CARBON MONOXIDE EMISSIONS
(g/kg)

Combustion equipment	Type of wood Seasoned oak	 Green oak	 Seasoned pine	 Green pine
Fireplace[a]	40 19	26 18	11 38 15	15
Baffled stove[b]	110	110 130	270 270	180 260
Nonbaffled stove[b]	370	87 77 109	150	110 99 83 83 110

[a] As determined by Dräger tube analysis of a bag sample.

[b] As determined by Orsat analysis; average of 10 grab samples.

Although it appears that the emission rates for the wood burning stoves are higher, a statistical analysis does not support this conclusion (see Appendix B). According to this analysis an unaccounted for variable exerted significant influence on the CO emission rates. Formulation of CO is apparently very sensitive to changing fuel bed conditions, and this may account for the variability between replicate test results. Figure 15 presents CO concentrations in the flue gas from a wood-burning stove versus time over one combustion cycle.

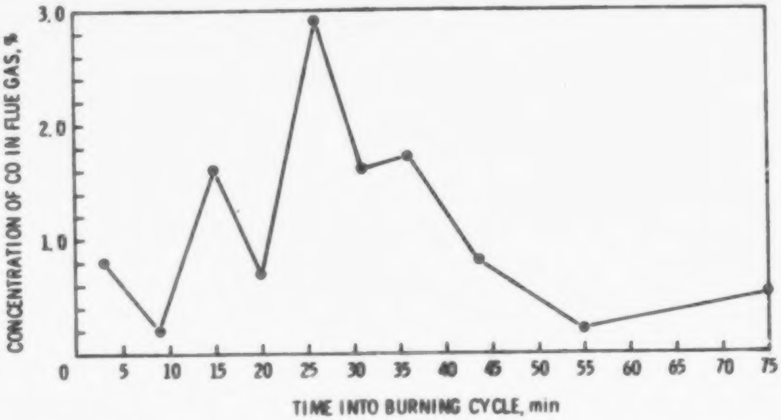

Figure 15. Carbon monoxide concentration in the flue gas from a wood-burning stove as a function of time.

This graph shows greater than an order of magnitude change in CO concentration in 20 minutes. With this high variability in one burning cycle, consistent results between series of tests should not be expected. The average CO emission rates, expressed as grams of pollutant emitted per kilograms of wood burned, in Table 17 represent the average of 10 grab samples taken in one burning cycle for the wood-burning stoves and a 15-min to 30-min integrated sample for the fireplaces. The results for the individual grab samples follow the general trend shown in Figure 15 and can be found in Appendix A.

Sulfur Oxides

Sulfur oxide emissions were anticipated to be very low because of the low fuel sulfur content (0.01%). Therefore, only two samples were collected for SO_2 analysis. Both samples were taken from the nonbaffled stove. The results are presented in Table 18 as SO_2 emission rates, expressed as grams of pollutant emitted per kilograms of wood burned.

Based on the fuel sulfur content the maximum possible SO_2 emission rates would be approximately 0.2 g/kg. The average measured SO_2 emission rate of 0.2 g/kg is in obvious agreement, TABLE 18. SO_2 EMISSIONS FROM THE NON-BAFFLED WOODBURNING STOVE

Wood type	Emission rate, g/kg
Seasoned oak	0.16
Seasoned pine	0.24

but each individual measurement differed by 20%. High variability would be expected because the fuel sulfur analysis and SO_2 analysis were both near the detection limit.

Low-Molecular-Weight Volatile Hydrocarbons

Low-molecular-weight volatile hydrocarbon emissions were determined by GC/FID from bag samples of flue gas collected over a 15-min to 20-min interval at four test conditions. The emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, for individual species are reported in Table 19. No additional effort was made to quantify these emissions because of the added labor requirements and the relatively lower environmental impact anticipated when compared to the higher-molecular-weight organics. Significant effort was expended in quantifying high-molecular-weight organic emissions as discussed later in this section.

The emission rates indicate high variability, in agreement with previous studies where total volatile hydrocarbon emission rates from fireplaces ranged from 2 g/kg to 400 g/kg (1, 2).

Major Organic Species

Emissions of organic material greater than C_6 were collected for analysis by the POM train and the SASS train, both of which employed an XAD-2 resin trap. The collected organic material was extracted from the XAD-2 resin and the remainder of the sampling train and submitted for analysis by GC/MS. The details of this procedure are presented in Section 3. The organic material could only be partially characterized because a major part was nonchromatographable by GC/MS.

As explained in Section 3, the organic loading of each sampling system during testing was quite high in spite of the reduced volume of sample collected. As a result large quantities of organic materials had to be recovered from various components of the sampling system. In all cases a significant quantity of organic matter was trapped in the aqueous impingers after passing through the filter and XAD-2 resin trap. That which was recovered from the resin and the particulate fractions would only partially dissolve in hexane during the sample workup. A portion of this insoluble material was soluble in methylene chloride, but there

TABLE 19. LOW-MOLECULAR-WEIGHT HYDROCARBON EMISSIONS[a] (g/kg)

Emission species	Fireplace seasoned oak	Baffled stove seasoned pine	Nonbaffled stove Green oak	Nonbaffled stove Green pine
Methane, CH_4		0.5		
C_1 to C_2 hydrocarbons		0.2	0.02	
Ethylene, C_2H_4	0.5	0.3		
Ethane, C_2H_6		0.1		
C_2 to C_3 hydrocarbons				
Propylene, C_3H_6		0.08		
Propane, C_3H_8		0.08		2.4
C_3 to C_4 hydrocarbons		0.5		
Butylene, C_4H_8				0.04
Butane, C_4H_{10}				
C_4 to C_5 hydrocarbons	15	0.5		0.6
Pentene, C_5H_{10}	<0.08			
Pentane, C_5H_{12}				
C_5 to C_6 hydrocarbons	2.6		0.3	
Hexene, C_6H_{12}				
Hexane, C_6H_{14}				
$>C_6$ hydrocarbons	0.5	0.5		
Total	19	2.8	0.3	3.0

Note: Blanks indicate emissions not detected.

[a] Determined by GC/FID at test site.

remained an insoluble solid white residue. Table 20 presents the mass of organic material recovered for GC/MS analysis. It was found that the hexane-soluble fraction was totally chromatographable while the methylene chloride fraction of hexane-insoluble material was largely nonchromatographable. The chromatographable portion, however, did contain approximately 50% of the POM compounds recovered from the total system. The nonchromatographable portion was indicated to be largely high molecular weight fused-ring aromatics (e.g., POM's, MW greater than 302).

The organic material recovered from the aqueous portion of the sampling train was for the most part nonchromatographable. Ions associated with organic acids were found and determined to be of molecular weight greater than 284, e.g., stearic acid. The detection limit of GC/MS for organic acids is quite high and their presence may go undectected.

Emission rates, expressed as grams of pollutant emitted per kilogram of wood, burned, for the major organic species, except POM's (see Table 23), identified by GC/MS are presented in Tables 21 and 22. Because of limitations in the recovery, separation and

TABLE 20. MASS OF ORGANIC MATERIAL RECOVERED FOR GC/MS ANALYSIS (g)

Test run conditions		Sampling system train	Sample fraction			
				Hexane-insoluble		
Combustion equipment	Wood type		Hexane-soluble	Methylene chloride-soluble	Solid residue	Aqueous extract
Fireplace	Seasoned oak	POM	0.135	-[a]	-[a]	0.016
Fireplace	Seasoned oak	SASS	0.301	1.07	-[a]	16.8
Fireplace	Green pine	POM	0.183	0.088	-[a]	0.042
Baffled stove	Seasoned oak	POM	0.190	0.566	0.105	1.86
Baffled stove	Seasoned pine	POM	0.341	0.241	0.096	0.090
Nonbaffled stove	Seasoned oak	POM	0.272	0.326	-[a]	0.239
Nonbaffled stove	Green pine	POM	1.04	0.142	-[a]	0.205
Nonbaffled stove	Green pine	SASS	6.95	4.29	-[a]	-[b]

[a] No material recovered in this fraction.

[b] The SASS train impinger contents and condensate were used for trace element analysis.

identification of organic compounds, the nature of the fuels and the combustion process, other species may have been emitted and escaped detection. However, many compounds of environmental interest (i.e., POM's) have been identified and quantified.

Table 21 presents the emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, for major organic species emitted, other than POM's, for four test conditions. The POM train and SASS train were both employed for collection of these species and the results are reported separately in the table. Over 50 organic species were identified, in addition to POM compounds, in the flue gas from wood-burning stoves and fireplaces. Specific organic acids (i.e., actetic acid, formic acid, etc.) were not identified because of the very high detection limit, but their presence was expected and has been substantiated as mentioned earlier. Generally speaking, the organic species identified were dominated by the naphthalenes, furans, phenols, cresols, and aldehydes. Total organic emission rates based on individual speciation for each condition ranged from 0.2 g/kg to 2.9 g/kg including POM's. A comparison of these values to the emission rates for condensable organic material (2.2 g/kg to 14 g/kg) presented earlier reveals that approximately 85% of the condensable material was not identified by GC/MS. This is in general agreement with the earlier discussion (see Table 20) regarding the large amount of nonchromatographable organic material.

TABLE 21. MAJOR ORGANIC SPECIES EMISSIONS

(g/kg)

	Fireplace			Baffled stove		Nonbaffled stove		
	Seasoned oak		Green pine	Seasoned oak	Seasoned pine	Seasoned oak	Green pine	
Major organic species identified	POM train	SASS train	POM train	POM train	POM train	POM train	POM train	SASS train
Ethyl benzene/xylenes	0.0059		0.0123	0.0129	0.0043	0.0342	0.1148	
Indane	0.0023		0.0070	0.0123	0.0136	0.0623	0.0421	
Indene	0.0189		0.0166	0.0394	0.0571	0.0643	0.1369	0.00085
Methyl indanes	0.0315		0.0319	0.0317	0.0815	0.0248	0.0230	0.0012
Methyl indenes	0.0151		0.0094	0.0324	0.0229	0.0264	0.0329	
Napthalene	0.0623	0.0076	0.0526	0.2729	0.2356	0.3078	0.4393	0.0070
Methyl-naphthalenes	0.0082	0.0046	0.0084	0.0700	0.0513	0.0311	0.0816	0.0029
C$_2$-alkyl-naphthalenes	0.0069	0.0038	0.0052	0.0290	0.0214	0.0209	0.0564	0.0033
Biphenyl	0.0027	0.0012	0.0029	0.0228	0.0193	0.0220	0.0139	0.0007
Acenaphthylene	0.0110	0.0063	0.0127	0.0754	0.0792	0.0561	0.0463	0.0055
Acenaphthene	0.0014	0.0007	0.0016	0.0069	0.0076	0.0097	0.0132	0.0006
Benzo furan				0.0150	0.0083			
Dibenzo furan		0.0032	0.0062	0.0365	0.0355	0.0460	0.0008	0.0026
Fluorene	0.0041	0.0032	0.0068	0.0224	0.0243	0.0238	0.0011	0.0026
Anthracene/phenanthrene	0.0096	0.0120	0.0146	0.0729	0.0754	0.0842	0.0939	0.0058
Phenol	0.0110	0.0185	0.0348	0.1265	0.0926	0.0442	0.3616	0.011
Cresols	0.0219	0.0601	0.0845	0.1477	0.1379	0.2107	0.4170	0.0363
C$_2$-alkyl phenols	0.0123	0.0387	0.0470	0.0949	0.0594	0.0720	0.1512	0.0282
C$_3$-alkyl phenols		0.0179	0.0280	0.0343	0.0134	0.0198	0.0620	0.0148
C$_4$-alkyl phenols		0.0131	0.0157	0.0122				0.0012
Benzaldehyde		0.0004	0.0029	0.0233	0.0167	0.0093	0.0092	0.0002
C$_1$-alkyl benzaldehyde		0.0005	0.0035	0.0131	0.0203	0.0174	0.0413	0.0015
C$_2$-alkyl benzaldehyde		0.0015	0.0249	0.0075	0.0208		0.0918	0.0033
C$_3$-alkyl benzaldehyde		0.0040	0.0105	0.0041	0.0068	0.0106	0.0413	0.0027
Methyl furans		0.0014		0.0060	0.0120	0.0137	0.0689	
C$_2$-alkyl-furans/furfural		0.0010		0.0053	0.0146	0.0398	0.1148	
C$_3$-alkyl-furans/methylfurfural		0.0047		0.0004	0.0130		0.0734	
C$_4$-alkyl-furans/C$_2$-alkylfurfural /methoxy phenols		0.0076						
Catechol		0.0073	0.0211		0.0099	0.0129	0.0067	0.0057
Naphthol		0.0059	0.0034		0.0086	0.0159	0.0038	0.0044
Methoxy phenols		0.0147	0.0055			0.0047	0.0022	0.0121
Methyl methoxy phenols		0.0152	0.0094			0.0042	0.0037	0.0212
C$_2$-alkyl methoxy phenols		0.0022	0.0099			0.0025	0.0038	0.0227
C$_3$-alkyl methoxy phenols		0.0134	0.0066				0.0023	0.0125
C$_4$-alkyl methoxy phenols		0.0412	0.0679			0.0136	0.0145	0.0541
C$_5$-alkyl methoxy phenols		0.0496						
Fluorenone		0.0011	0.0004	0.0034	0.0019	0.0041	0.0004	0.0006
Fluorenone isomer		0.0011	0.0005	0.0049	0.0038	0.0061	0.0008	0.0008
Anthrone		0.0011	0.0008	0.0023	0.0034	0.0050	0.0011	0.0010
Benzanthrone				0.0021	0.0017	0.0023		
Dimethoxy phenol		0.0987	0.0018			0.0063		0.0023
Hydroxy methoxy benzaldehyde		0.0228	0.0144			0.0103	0.0057	0.0129
Hydroxy methoxy acetophenone		0.0125	0.0097			0.0051	0.0053	0.0079
Hydroxy methoxy benzoic acid		0.0607						
Hydroxy dimethoxy benzaldehyde		0.0402						
Hydroxy dimethoxy acetophenone		0.0135						
Hydroxy dimethoxy cinnamaldehyde		0.0125			0.0056			0.0006
C$_2$-alkyl biphenyls (or isomers)		0.0231						
C$_3$-alkyl biphenyls (or isomers)		0.0116						
C$_4$-alkyl biphenyls (or isomers)		0.0328						
Di-C$_8$ alkyl-phthalate		0.0011		0.0002	0.0011	0.0007	0.0002	0.0038
Aliphatics			0.0435				0.0038	
Total	0.2251	0.6941	0.6349	1.2407	1.1178	1.3448	2.583	0.295

Note: Blanks indicate emission factor not identified.

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By use of a direct injection probe (DIP), it was determined that a large fraction of the material that collected in the water impingers was organic (aliphatic) acids of a rather high molecular weight range, probably greater than 284 molecular weight (i.e., stearic acid). The remaining fraction of nonchromatographable material was also examined by DIP probe technique and showed a continuous stream of ions, many above 302 atomic mass units (dibenzopyrene). This suggests emissions of a variety of high molecular weight fused ring aromatics (i.e., POM's, MW greater than 302).

The emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, presented in Table 21 suggest that for species other than POM's the combustion equipment and wood type had little effect on the individual emission rates. The results of the two SASS train runs deserve some comment. Tests conducted on the fireplace using the SASS train and POM train compare reasonably well for compounds identified in both trains. It is not expected that a close correspondence would exist because of the difference in sampling times and sample volumes between the two trains. Many more compounds were identified in the SASS train sample, which is understandable because its larger sample volume provides more material for analysis. This is most obvious in the fireplace samples where the flue gas is much more dilute than the flue gas from the stoves. Because of the additional species identified, the total emission rate for chromatographable species calculated from the SASS train is about 3 times greater than that calculated from the POM train.

The remaining SASS run was conducted on the nonbaffled stove burning green pine. Compared to the corresponding POM train run the SASS train results are about an order of magnitude lower instead of higher as expected. The apparent explanation for this discrepancy is that XAD-2 resin in the SASS train was overloaded during sampling. The data in Table 20 were used to prepare Table 22 showing the organic loading of the XAD-2 resin for all of the POM train and SASS train runs.

Although the organic loading of the SASS run in question does not appear higher than in the run performed on the fireplace, it does not reflect the fact that the organic material collected in the impinger and the condensate was not recovered. In the SASS run on the fireplace in Table 20, presented earlier, the organic material passing through the resin and trapped in the aqueous components is 92% of the total organic loading. If this same ratio is applied to the SASS run on the nonbaffled stove, the mass of organics passing through the resin and trapped in the impingers and condensate would be about 140 grams. This corresponds to an organic loading of 121 percent of the virgin XAD-2 resin weight. An organic loading of much less than this would overload the XAD-2 resin, indicating that overloading may have occurred in some of the runs. This would explain the observed low emission rates.

TABLE 22. ORGANIC LOADING OF POM TRAIN AND SASS TRAIN

Combustion equipment	Wood type	Sampling system train	Organic loading, % of virgin XAD-2 resin
Fireplace	Seasoned oak	POM	1
Fireplace	Seasoned oak	SASS	15
Fireplace	Green pine	POM	2
Baffled stove	Seasoned oak	POM	1.5
Baffled stove	Seasoned pine	POM	4
Nonbaffled stove	Seasoned oak	POM	4
Nonbaffled stove	Green pine	POM	7
Nonbaffled stove	Green pine	SASS	>9[a]

[a] The impinger contents and condensate from this run were used for trace element analysis and the organic contents are therefore unknown.

Because XAD-2 resin selectively adsorbs organic species at varying rates, different organics break through at different times as the resin becomes overloaded. A highly sensitive technique for screening POM's was used on one SASS run used to collect samples for bioassay (baffled stove burning seasoned oak). Test samples were taken from the sampling train before and after the XAD-2 resin (specifically the rinse of the XAD-2 module and the aqueous condensate). The results showed no POM's present after the XAD-2 resin, and indicated that POM breakthrough did not occur. The consistency of POM results from all runs on woodburning stoves, except the SASS run previously discussed, indicate that POM breakthrough probably did not occur. Because the fireplace flue gas was much more dilute, there is greater certainty that POM breakthrough did not occur on the fireplace runs.

Emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, for individual POM compounds and total POM's are presented in Table 23. Wood type does not appear to significantly influence POM emissions, but the total POM emission rate was an order of magnitude lower for the fireplace than for the woodburning stove. This is consistent with the CO and NO_x results, which indicate more efficient combustion and/or higher combustion temperature in the fireplace. Comparison of the SASS train results with those from the POM train for POM emissions follows the same pattern as was discussed earlier for major organic species and need not be reported.

In a previous study on the emissions from coal-fired residential combustion system high concentrations of the POM compound 7,12-dimethylbenzanthracene (DMBA) or its isomers (i.e., C_2-alklybenzanthracenes/benzphenanthrenes/-chrysenes) were found in the flue gas (12). This compound is known to be a strong animal carcinogen, and its potential presence in combustion flue gases is of concern to the EPA. The EPA, therefore, requested Arthur D. Little, Inc., to verify the test results; the EPA also submitted an audit sample to MRC containing DMBA. Preliminary results from Arthur D. Little have confirmed the presence of DMBA. The audit sample results are presented in Appendix C.

TABLE 23. POM EMISSIONS
(g/kg)

POM compounds	Fireplace			Baffled stove		Nonbaffled stove		
	Seasoned oak		Green pine	Seasoned oak	Seasoned pine	Seasoned oak	Green pine	
	POM train	SASS train	POM train	POM train	POM train	POM train	POM train	SASS train
Anthracene/phenanthrene	0.0082	0.0114	0.0069	0.0745	0.1463	0.0618	0.1034	0.0104
Methyl-anthracenes/-phenanthrenes	0.0027	0.0034	0.0083	0.0211	0.0510	0.0167	0.0513	0.0028
C_2-alkyl-anthracenes/-phenanthrenes	<0.0014[a]	0.0011	0.0014	0.0040	0.0070	0.0045	0.0094	0.0008
Cyclopenta-anthracenes/-phenanthrenes	<0.0014[a]	0.0004	0.0014	0.0032	0.0086	0.0030	0.0047	0.0002
Fluoranthene	<0.0014[a]	0.0026	0.0016	0.0180	0.0316	0.0208	0.0188	0.0012
Pyrene	<0.0014[a]	0.0026	0.0016	0.0156	0.0240	0.0169	0.0188	0.0013
Methyl-fluoranthenes/-pyrenes	<0.0014[a]	0.0023	0.0016	0.0128	0.0167	0.0103	0.0142	0.0016
Benzo(ghi)fluoranthene		0.0009	0.0014	0.0048	0.0067	0.0047	0.0047	0.0004
Cyclopenta[ed]pyrene	<0.0014[a]	0.0010	0.0014	0.0048	0.0089	0.0051	0.0138	0.0005
Benzo(c)phenanthrene		0.0004	0.0013	0.0016	0.0023	0.0016	0.0046	0.0002
Benz(a)anthracene/chrysene	<0.0014[a]	0.0020	0.0014	0.0125	0.0138	0.0076	0.0371	0.0013
Methyl-benzanthracenes -benzphenanthrenes/-chrysenes	<0.0014[a]	0.0013	0.0016	0.0062	0.0104	0.0062	0.0048	0.0009
C_2-alkyl-benzanthracenes/ -benzophenanthrenes/ -chrysenes		0.0009	0.0014	0.0055	0.0044	0.0037	0.0047	0.0005
Benzofluoranthenes	<0.0014[a]	0.0022	0.0016	0.0128	0.0159	0.0112	0.0141	0.0015
Benzopyrenes/perylene	<0.0014[a]	0.0017	0.0014	0.0083	0.0116	0.0084	0.0094	0.0011
Methyl cholanthrene				0.00007				
Indeno(1,2,3-ed)pyrene Benzo(ghi)perylene		0.0013	0.0015	0.0045	0.0099	0.0043	0.0048	0.0011
Anthanthrene Dibenzanthracenes/-phenanthrenes		0.0003	0.00005	0.0007	0.0014	0.0010	0.00005	0.0002
Dibenzocarbazoles Dibenzopyrenes		0.0007	0.0001	0.0011	0.0010	0.0007	0.00002	0.0005
Total[b]	0.0249	0.0365	0.0360	0.2121	0.3715	0.1885	0.3187	0.0265

Note: Blanks indicate POM compound not detected.

[a] Compound was identified but not quantified because of the detection limits of the analytical method.

[b] The detection limit was taken as the emission factor for compounds that were identified but not quantified.

Isomers of DMBA have also been found in this program on wood-fired combustion systems, although, they represent less than 5% of the total POM mass emitted. The lower-molecular-weight POM compounds were found to exist in the highest concentration.

Because formaldehyde and certain other aldehydes were not expected to be identified by GC/MS but were anticipated to be present in the flue gas, a separate sampling train was employed specifically for these compounds.

Table 24 presents the results of the aldehyde analysis as emission rates, expressed as grams of pollutant emitted per kilogram of wood burned. Three trains were employed at each test condition, and flue gas samples were collected for approximately 20 min to 30 min in each case. The average of the 3 sets of results for each test condition are more representative than the individual tests because of the short sampling times. As was the case

TABLE 24. ALDEHYDE EMISSIONS
(g/kg)

	Fireplace	Baffled stove	Nonbaffled stove	
Aldehyde type	Seasoned oak	Seasoned pine	Green oak	Green pine
Formaldehyde[a]	0.4 0.2 0.5	0.02 0.02 0.4	0.5 0.3 0.1	0.2 0.3 0.4
Average	0.4	0.1	0.3	0.3
Propionaldehyde[b]	-[c]		0.1 0.1	0.4 0.3
Average	-[c]		0.1	0.2
n-Butyraldehyde[b]	0.2	0.1 0.9 0.8	1.7	0.2 0.5
Average	0.1	0.6	0.6	0.2
Isobutyraldehyde[b]	1.4	0.2	0.1 0.5	2.1 10.7
Average	0.5	0.1	0.2	4.3
Acetaldehyde[b]		0.1	0.2	0.04 0.6 0.1
Average		0.03	0.1	0.2
Pentanol[b]		0.2 0.1	0.1	
Average		0.1	0.03	

Note: Blanks indicate emission species not detected.

[a] Analyzed by colorimetric technique employing chromotropic acid.

[b] Analyzed by GC/FID.

[c] The calculated emission rate was 570 g/kg; this is obviously erroneous but could not be readily attributed to any traceable error in calculation, analysis, or sampling.

for the organic species presented in Table 21, the aldehyde emission rates were not influenced by the combustion equipment or wood type. The apparently high or low emission rates for any one species are within the variability of the test results.

POM Screening Results

A method to screen for POM compounds present in flue gas emissions was employed in this program in an attempt to determine its utility for field application. The analytical method has been reported in the literature (19) and was discussed earlier in Section 3 along with the sampling technique. The results of the field screening are presented in Table 25 along with laboratory screening the field samples and the GC/MS results of the 6 POM train samples. Because of the semiquantitative nature of the screening technique, the results are presented as a range of possible values.

TABLE 25. FLUE GAS FROM POM CONCENTRATIONS BY UV FLUORESCENCE SCREENING[a] OF GRAB SAMPLES VERSUS CONVENTIONAL SAMPLING AND ANALYSIS ($\mu g/m^3$)[b]

Combustion equipment	Wood type	POM screening results: Field results	POM screening results: Laboratory test I	POM screening results: Laboratory test II	GC/MS results of POM train samples
Fireplace	Seasoned oak	430 - 4,300	220 - 2,200	220 - 2,200	450
Fireplace	Green oak	200 - 2,000	200 - 2,000	400 - 4,000	
Fireplace	Seasoned pine	40 - 430	40 - 430	20 - 220	
Fireplace	Green pine	410 - 4,100	410 - 4,100	210 - 2,100	530
Baffled stove	Seasoned oak	110 - 1,100	110 - 1,100	110 - 1,100	12,000
Baffled stove	Green oak	5,000 - 50,000	2,500 - 25,000	5,000 - 50,000	
Baffled stove	Seasoned pine	44,000 - 440,000	44,000 - 440,000	44,000 - 440,000	21,000
Baffled stove	Green pine	210 - 2,100	110 - 1,100	110 - 1,100	
Nonbaffled stove	Seasoned oak	60 - 600	20 - 200	40 - 390	9,800
Nonbaffled stove	Green oak	430 - 4,300	40 - 430	40 - 430	
Nonbaffled stove	Seasoned pine	20 - 220	20 - 220	20 - 220	
Nonbaffled stove	Green pine	430 - 4,300	20 - 220	40 - 430	16,000

Note: Blanks indicate no data were obtained.

[a] Test procedure was based on visual observation and was at best semiquantitative; as a result POM concentrations are expressed as a range. Agreement between laboratory and field measurements indicates reproducibility in observation of fluorescent intensity.

[b] Micrograms of POM per actual cubic meter of flue gas.

In all but two cases the laboratory observation of UV fluorescence on the screening samples was consistent with the field results. The quantitative flue gas concentrations as determined by GC/MS indicate that the screening technique produced reasonable results. In two cases the range of POM concentration determined by screening actually included the quantitative value, while in two other cases, the range missed the quantitative value by factors of 2 and 4. The remaining two cases differed by factors of 11 and 15. Of the four ranges that varied from the quantitative value, two were low and two were high. In the sampling method employed for screening flue gas was collected for only 30 to 60 minutes. Therefore, it was expected that some variability would exist between results obtained by this method and those obtained by the

POM train since flue gas samples were collected over 60 min to 120 min in the latter. Therefore, the cyclic nature of the wood-burning process makes the screening sample the least representative. However, considering that the sampling and analysis for the screening method was completed in the field in about 2 hours, the level of uncertainty may be an acceptable trade-off.

Bioassay Results

Bioassay results for the twelve SASS train runs and for the combustion residue samples (ash) are reported in Table 26 (31). Discussions of the results observed for each bioassay test are given in the following subsections. Specific test procedures can be found in a report prepared by Litton Bionetics, Inc., (LBI) for the EPA under a separate contract (31).

Ames Mutagenicity Assay--

The Ames Mutagenicity Assay test evaluates samples for genetic activity in the *Salmonella*/microsome plate assays with and without the addition of mammalian metabolic activation preparations. The genetic activity of a sample is measured in these assays by its ability to revert the *Salmonella* indicator strains from histidine dependence to histidine independence. The degree of genetic activity of a sample is reflected in the number of revertants that are observed on the histidine free medium.

The results shown in Table 26 show that all of the emission samples (twenty-four) tested exhibited mutegenic activity. None of the four samples of combustion residue showed mutegenic activity (31).

CHO Clonal Toxicity Assays--

This test determined the cytotoxicities of twenty-four residential wood combustion emission samples to cultured Chinese hamster cells (CHO-K1 cell line). The measure of cytotoxicity was the reduction in colony-forming ability after a 24-hour exposure to the test material. After a period of recovery and growth, the number of colonies that developed in treated cultures was compared to the colony number in unexposed vehicle control cultures. The concentration of test material that reduced the colony number by 50% was estimated graphically and referred to as the EC_{50} value (effective concentration for 50% survival). The toxicity of the test materials is evaluated as high, moderate, low, or nondetectable according to the range of EC_{50} values (Table 27).

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(31) Level I Bioassays on Thirty-Two Residential Wood Combustion Residue Samples. Contract 68-02-2681, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. (Final report submitted to the EPA by Litton Bionetics, Inc., November 1979). 211 pp.

TABLE 26. RESULTS OF BIOASSAYS PERFORMED ON SASS AND COMBUSTION RESIDUE SAMPLES (31)

			Bioassay test				
Sample code[a]	Combustion equipment	Wood type	Ames mutagenicity[b]	CHO clonal toxicity[c]	RAM[c]	Acute rodent quantal[c]	Freshwater daphnia[c]
A-1 (1)	Fireplace	Seasoned oak	+	H			
A-1 (2)	Fireplace	Seasoned oak	+	H			
A-1 (3)	Fireplace	Seasoned oak	-		L		
A-2 (1)	Fireplace	Green oak	+	H			
A-2 (2)	Fireplace	Green oak	+	H			
A-2 (3)	Fireplace	Green oak					ND
A-3 (1)	Fireplace	Seasoned pine	+	H/M			
A-3 (2)	Fireplace	Seasoned pine	+	H			
A-3 (3)	Fireplace	Seasoned pine				NT	
A-4 (1)	Fireplace	Green pine	+	H			
A-4 (2)	Fireplace	Green pine	+	H			
B-1 (1)	Baffled stove	Seasoned oak	+	M			
B-1 (2)	Baffled stove	Seasoned oak	+	H			
B-2 (1)	Baffled stove	Green oak	+	H			
B-2 (2)	Baffled stove	Green oak	+	H			
B-2 (3)	Baffled stove	Green oak	-		L		
B-3 (1)	Baffled stove	Seasoned pine	+	H			
B-3 (2)	Baffled stove	Seasoned pine	+	H			
B-3 (3)	Baffled stove	Seasoned pine	-		L		
B-4 (1)	Baffled stove	Green pine	+	H/M			
B-4 (2)	Baffled stove	Green pine	+	H			
C-1 (1)	Nonbaffled stove	Seasoned oak	+	H			
C-1 (2)	Nonbaffled stove	Seasoned oak	+	H			
C-2 (1)	Nonbaffled stove	Green oak	+	H			
C-2 (2)	Nonbaffled stove	Green oak	+	H			
C-2 (3)	Nonbaffled stove	Green oak				NT	
C-3 (1)	Nonbaffled stove	Seasoned pine	+	H			
C-3 (2)	Nonbaffled stove	Seasoned pine	+	H			
C-3 (3)	Nonbaffled stove	Seasoned pine					ND
C-4 (1)	Nonbaffled stove	Green pine	+	H			
C-4 (2)	Nonbaffled stove	Green pine	+	H			
C-4 (3)	Nonbaffled stove	Green pine	-				

Note: Blanks indicate samples were not submitted for testing.

[a] Corresponds to the following sample fractions: (1) particulate catch extract, supplied to LBI as methylene chloride solutions; (2) combined organic module rinse and XAD-2 extract, supplied to LBI as dimethyl sulfoxide solutions; (3) combustion residue (bottom ash), supplied to LBI as dry ash.

[b] "+" designates mutagenic activity; "-" designates no mutagenic activity.

[c] ND, no detectable toxicity; NT, not tested; L, low toxicity; M, moderate toxicity; H, high toxicity.

The cytotoxicity results indicated that the combined organic module rinse plus XAD-2 resin extracts were, as a group, more toxic than the particulate catch extracts. Within each group, the fireplace samples were either the least toxic or in the least toxic half of the test samples, and the nonbaffled stove extracts were generally the most toxic. No generalizations regarding the fuel source were apparent. Twenty-one of the twenty-four samples tested were considered highly toxic, the others were described as moderately toxic, or at the moderate-to-high toxicity borderline. These results are given in Table 26 (31).

TABLE 27. DEFINITION OF RANGE OF EC_{50} VALUES

Toxicity[a]	EC_{50} values, µg/L
High	<10
Moderate	10 to 100
Low	100 to 1,000
Nondetectable	>1,000

[a] Formulated by Litton Bionetics, Inc., under EPA Contract 68-02-2581, Technical Directive No. 301.

Rabbit Alveolar Macrophage (RAM) Cytotoxicity Assays--
This assay determined the cytotoxicities of four bottom ash samples to rabbit alveolar macrophages in short term culture. The cells were exposed to the test material for 20 hours and the following five cellular variables were measured: percent viability index, total protein, total ATP, and ATP content per 10^6 cells. Each parameter was compared to the corresponding value obtained for untreated control cell cultures. Then the concentrations of test material that reduced each parameter by 50% were estimated graphically and referred to as the EC_{50} values. This assay was limited to applied concentrations in the 3 µg/L to 1,000 µg/L range.

All four test materials (bottom ashes) were evaluated as having low toxicity to RAM cells because the most sensitive assay parameter (usually ATP content) yielded EC_{50} values in the 100 to 1,000 µg/L concentration range (31).

Level I Rodent Toxicity--
The Level I rodent toxicity test evaluates the acute toxicity of the test materials when administered orally to male and female rats. Attempts were made to test two combustion residue (ash) samples. This test was abandoned when it proved impossible to prepare a liquefied form of the combustion residue (31).

Freshwater Toxicity Assays--

Freshwater toxicity assay determines the toxicity of the combustion residue samples during 48-hour static exposure. The acute toxicities of two of the combustion residue samples were determined for the freshwater invertebrate *Daphnia magna*.

The toxicity of the test materials is evaluated as high, moderate, low, or nondetectable according to the range of EC_{50} values (Table 27). Both samples tested had nondetectable toxicity (31).

ENERGY EFFICIENCY TESTING

The energy efficiency of the combustion equipment tested in this program was measured by Auburn University. The efficiency of the wood-burning stoves was determined using a stack gas analysis technique (32). The useful heat lost in the flue gas plus the potential heat lost in combustible components of the flue gas were determined and subtracted from the heat released by the wood to arrive at a value for heat recovered and thus efficiency. The procedure was repeated at 2-1/2-min intervals throughout the burn of one charge of wood to observe the changes occurring during the combustion cycle and to arrive at an average efficiency. Actual calculations and various data correlations were performed by computer. Appendix A presents the computer printouts of the raw data and of calculated results from efficiency testing. The results are summarized in Table 28.

Fireplace efficiencies cannot be determined by this method because of the large volume of ambient air drawn into the fireplace flue which dilutes the combustion gases. Previous tests conducted in a calorimeter room on the fireplace resulted in a maximum efficiency of 23%. Since there were no combustion air controls on the fireplace and since it was operated in this study with the heat recovery system turned on, it is reasonable to assume that the efficiency of this fireplace remained fairly stable and near its peak during testing.

Wood-burning stove efficiencies ranged from 22% to 52%, averaging about 45%. Essentially no difference was seen between the baffled and nonbaffled stove efficiencies. Higher efficiencies might be achievable under different modes of operation such as a starved air condition.

---

(32) Maxwell, T. T., D. F. Dyer, and G. Maples. Efficiency and Heat Output Measurements for Residential Wood Heating Appliances. In: Wood Heating Seminar 6, Wood Energy Institute, Chicago, Illinois, February 1980. pp. 119-228.

TABLE 28. SUMMARY OF EFFICIENCY TEST DATA OBTAINED ON THE BAFFLED AND NONBAFFLED WOOD-BURNING STOVES

Combustion device	Wood type	Efficiency,[a] %		Average excess air, %	Combustion air vent settling		Flue gas temperature, °C		Total wood charge, kg	Average burning rate, kg/hr
		Average	Range		Top vent[b]	Bottom vents[c]	Average	Range		
Baffled stove	Seasoned oak	34	16 - 43	160	Full open	Full open	310	170 - 391	13.5	7.3
Baffled stove	Seasoned oak	37	30 - 43	92	Open 2 turns	Open 2 turns	328	266 - 385	13.5	7.3
Baffled stove	Green oak	45	37 - 56	99	Open 1 turn	Open 2 turns	272	204 - 354	11.2	6.8
Baffled stove	Seasoned pine	52	46 - 61	17	Open 1 turn	Full open	372	275 - 401	9.1	10.9
Baffled stove	Seasoned pine	48	38 - 62	21	Open 1 turn	Open 2 turns	321	225 - 359	9.4	9.9
Baffled stove	Green pine	49	39 - 59	96	Open 1 turn	Full open	324	144 - 428	6.0	9.7
Baffled stove	Green pine	44	35 - 54	91	Open 1 turn	Full open	326	241 - 461	8.6	8.1
Nonbaffled stove	Seasoned oak	43	28 - 52	25		Open 1.5 turns	413	166 - 426	11.7	9.9
Nonbaffled stove	Green oak	37	23 - 50	200		Open 2.5 turns	297	177 - 443	13.1	8.6
Nonbaffled stove	Green oak	22	18 - 39	211		Open 2 turns	390	208 - 599	13.4	7.3
Nonbaffled stove	Green oak	48	40 - 65	73		Open 2 turns	324	227 - 372	9.2	8.4
Nonbaffled stove	Seasoned pine	47	46 - 64	58		Open 1 turn	282	186 - 485	10.8	7.1
Nonbaffled stove	Green pine	39	31 - 55	86		Open 2.5 turns	320	169 - 569	9.1	8.4
Nonbaffled stove	Green pine	48	42 - 55	42		Open 3 turns	437	206 - 581	6.4	10.2
Nonbaffled stove	Green pine	51	34 - 64	68		Open 1.5 turns	326	180 - 428	11.1	8.4
Nonbaffled stove	Green pine	33	11 - 49	135		Open 2 turns	315	182 - 443	11.0	6.9
Nonbaffled stove	Green pine	49	40 - 57	51		Open 2.5 turns	410	223 - 566	9.2	8.2

Note: Blanks indicate data not applicable.

[a] Average and range of one test burning one wood charge.

[b] Provides secondary combustion air.

[c] Provides primary combustion air.

SECTION 5

DISCUSSION OF RESULTS AND CONCLUSIONS

The preceding section presented test results from the sampling of emissions from three wood-fired residential combustion systems. The effect of certain test variables on individual emission species was also observed and discussed. This section examines more general correlations among the test parameters and draws certain tentative conclusions from the data.

EFFECT OF COMBUSTION EQUIPMENT

Three combustion units were tested during this study: a residential fireplace, a baffled wood-burning stove, and a nonbaffled wood-burning stove. A number of differences were noted in the emissions from the stoves versus the fireplace. Both stoves, however, behaved similarly. Carbon monoxide and POM emission rates, expressed as grams of pollutant per kilogram of wood burned, were an order of magnitude higher from the stoves than from the fireplace, while NO_x emission rates averaged four times higher from the fireplace. Because of the scatter in the data and the limited number of tests, only the NO_x emission rates were statistically different. No trends were noted in emissions of particulate matter and hydrocarbons, although a high variability was evident in the test results.

These results suggest that conditions were more favorable for complete combustion in the residential fireplace. Indeed, an examination of the wood-burning rate reveals that wood was consumed in the fireplace at a rate 40% greater than in the stoves, evidence of a hotter fire and better combustion. Both carbon monoxide and POM's are products of incomplete combustion, and they would be expected to be emitted in greater amounts under poorer combustion conditions. It is unclear, though, why particulates and hydrocarbons do not also exhibit higher emission rates from the stoves, since they too form as a result of incomplete combustion. It is possible that the high variability in the data has obscured the true situation. Additional sampling would be needed to verify this supposition.

Emissions of NO_x depend primarily on combustion temperatures so long as sufficient excess air is present for complete combustion. Thus it is not surprising that higher NO_x emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, occurred in the fireplace tests where hotter temperature prevailed.

No significant differences were noted in emissions between the two air-tight stoves tested during this program. The baffled stove was designed to improve combustion efficiency by providing longer retention time, a secondary combustion zone, and secondary combustion air. These features are designed to allow combustion of organic material escaping from the primary combustion zone. Under the test conditions in this program the baffled stove provided no improvements in combustion as evidenced by the emission rates and energy efficiencies.

Wood-burning stoves can be operated under starved air conditions by closing the air vents in the stove doors, a practice followed by some people to extend the burning cycle. However, in this program, tests were conducted on stoves operated with an adequate supply of combustion air. Under starved air conditions the wood-burning unit acts more like a wood gasifier or pyrolysis device, and causes creosote[a] formation and build-up in the flue pipes. Creosote formation is a fire hazard because of the potential for ignition of the accumulated build-up. For this reason those organizations promoting wood heating are educating the public in this area, and are discouraging operation at the starved air condition. More important to emission testing is the difficulty in obtaining and characterizing representative samples during starved air burning. Higher organic emissions can cause sampling trains to become overloaded and fouled unless they are operated for very short time intervals. Because of low air flow, flue gas velocity becomes almost impossible to measure. Finally, complex sample matrices become monumental analysis tasks. The end result can easily be a long and costly test program yielding questionable data. With this in mind, no testing was done in the current program under starved air conditions, even though some stoves are operated in this manner and are expected to produce higher levels of organic emissions.

EFFECT OF WOOD TYPE

Of the four woods burned in this program, only yellow pine in the green state had any noticeable effect on emissions. Particulate, condensable organic, and POM emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, were all higher when burning green pine, but usually by less than a factor of 3. Examination of the fuel analysis (see Table 4) does not reveal any significant difference in the basic chemical components of the green pine. In all cases the composition is either close to all of the other woods, or close to at least one other wood. A difference would probably be found upon a more detailed chemical analysis of the volatile portion of the wood. It has been reported that softwoods contain from 0.8% to 25% resinous material while hardwoods contain only 0.7% to 3% (10). The combination of the high resin content and high moisture of the green pine apparently influences the emissions generated when burning this wood type. It has been suggested that particulate emission rates, expressed as grams of pollutant emitted per kilograms of wood burned, (including the condensable organics) are directly affected by initial fuel charge and inversely affected by the combustion rate corrected for moisture (5).

---

[a] The term creosote, although not technically correct, is commonly used to describe the condensed resinous material collected on chimney and flue pipe walls.

EFFECT OF WOODBURNING CYCLE

Residential wood burning in fireplaces and stoves is cyclic in nature, not only because it is a batch process but also because wood burns in stages. Briefly the burning stages are drying, distillation of volatile matter, and burning of carbonaceous residue. All three stages occur simultaneously, however, drying and distillation dominate early in the burn of a single charge of wood. Figure 16 illustrates the variation in flue gas temperature during the performance of one SASS train run on a woodburning stove measured 0.8 m from the flue gas exit. The wide variation in temperatures and cyclic nature are indicative of the nature of the combustion process.

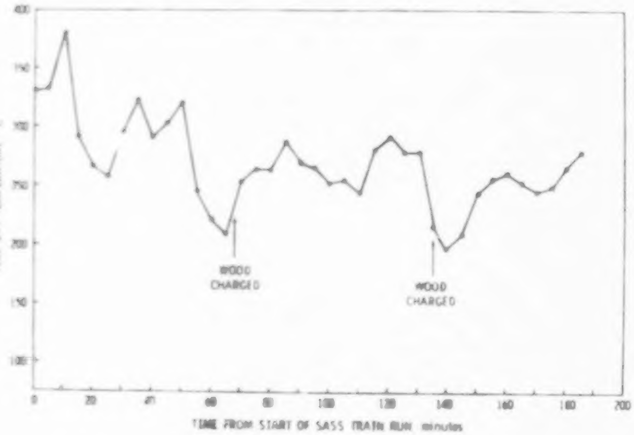

Figure 16. Flue gas temperature versus time for the nonbaffled stove burning seasoned oak.

Basic combustion products (CO, CO_2, and H_2O) have been shown to cycle through the burn of one wood charge earlier in this section. More complete data are given in Appendix A. Others have shown that particulate emissions also cycle during the wood buring process as demonstrated in Figure 17 (5). It would therefore be

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reasonable to assume that organic species such as POM's would also cycle, being emitted at a higher rate during the early part of a burn. A more extensive sampling program would be required to measure this phenomenon.

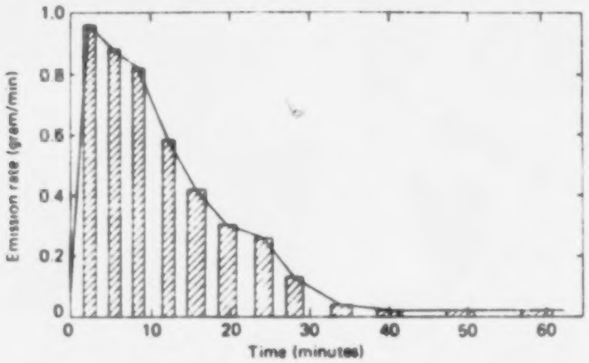

Figure 17. Particulate emissions during the combustion of 2.27 kg of oak (5).

EFFECT OF CREOSOTE DEPOSITION ON REPRESENTATIVE SAMPLING

Because sampling probes were not located directly at the flue gas discharge point, there was a question whether some of the emissions sampled would normally condense onto the flue pipe wall instead of being released to the atmosphere. Unpublished tests conducted at the Auburn Woodburning Laboratory using an air-tight stove show that the flue gas must be cooled to 125°C to 155°C before significant amounts of creosote condense within the stack. Because flue gas temperatures rarely dropped below this limit during emission testing, it is believed that the samples collected represent the actual emissions. This was verified by examination of the flue pipe which revealed a minimum deposit of soot. As mentioned earlier, however, creosote formation can be expected when stoves are operated under starved air conditions.

GENERAL REMARKS AND CONCLUSIONS

This investigation is the most comprehensive program undertaken to characterize emissions from residential wood-burning devices. Nevertheless, test results apply only to the equipment and fuels tested and only under the operating conditions employed in this program. Caution should be exercised in extrapolating these results to other test conditions. Because data obtained in this study are in general agreement with other studies of this source type, a certain degree of extrapolation may be justified. Further studies to examine the effect of variables such as wood geometry, firing rate, air-fuel ratio, combustion temperature, design, ambient conditions, and secondary air is recommended to provide more information on emission variables.

The results of previous studies on fireplace for the most part are supported by this program; however, the scope of those studies was not as comprehensive. One study performed in Vail, Colorado, on fireplace emissions reported significantly higher emission rates, expressed as grams of pollutant emitted per kilogram of wood burned (2). High altitude has been suggested as a possible cause of this difference. Experts in the combustion area consider this explanation highly unlikely, and it is probably due to some other variable. No studies to date have quantified emissions from air-tight stoves under starved air conditions. Because of the many variables associated with air-tight stoves, a more extensive study would be necessary to examine this type of operation. It is reasonable to assume that reducing the rate of combustion will produce higher emission levels unless there is some provision in the stove design which favors complete combustion of evolved organics. The baffled stove design apparently is not achieving this goal as intended.

Because of the nature of the residential wood combustion process (large pieces of fuel, highly resinous fuel, uneven fuel distribution, and hand-feeding in batches), the actual instantaneous combustion efficiency is lower than in most other conventional combustion systems. Thus, organic emissions are relatively high. Because the organic emissions include a number of potentially hazardous compounds (aldehydes, POM's, etc.), the trend toward greater residential wood usage may have a significant impact on local air quality. The emphasis on wood combustion in air-tight stoves as an alternate energy source may greatly increase the magnitude of the problem. The environmental impact of this problem needs to be evaluated and emphasis needs to be placed on sound engineering design of wood-burning equipment so that the desired energy efficiency can be obtained in an environmentally acceptable manner.

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APPENDIX A

THERMAL EFFICIENCY TEST DATA FOR THE BAFFLED AND NONBAFFLED WOODBURNING STOVES

Thermal efficiency tests were conducted by Auburn University during the emission testing program. Timing of individual efficiency tests was not always synchronized with emission testing because of the length of the emission testing and the need for an undisturbed system during efficiency testing. Efficiency test data were analyzed by computer to determine the thermal efficiency and other combustion parameters. The computer also calculated various other correlations.

The computer output for the thermal efficiency determination contains the following information at specific times of the wood burning cycle: mass of unburned wood, flue gas temperature, percent CO_2, percent O_2, percent CO, percent combustibles, percent efficiency, air-fuel ratio, theoretical air and heat release rate. The following correlations are also provided by the computer output and are presented in this Appendix:

(1) Percent efficiency versus heat release
(2) Flue temperature versus time
(3) Percent CO_2, O_2, CO and combustibles versus time
(4) Air-fuel ratio versus time
(5) Heat release versus time
(6) Weight wood unburned versus time
(7) Percent efficiency versus time

In many instances the curves are off scale. Auburn University's computer program is equipped to handle small charges of wood and the scales employed could not accomodate the larger charges used during this test program.

```
                 WOOD BURNING TEST RESULTS   B-1
                                                  POM Screen
TEST NUMBER    :  1-3/14/79

DATE OF TEST   :  MARCH 14, 1979

AMBIENT TEMPERATURE :      75  DEG F

DAMPER SETTING :
                       FULL OPEN /ALL THREE

FUEL :  SPLIT RED OAK 4 PIECES        B-1

MOISTURE CONTENT  30.0 %            HHV=    -6174.7


  TIME   LBS WOOD FLUE GAS %CO2  %O2   %CO  %COM %EFF  A/F    THEO  HEAT RLSE
                  TEMP (F)                              RATIO   AIR    BTU/HR

   0   0   29.8     336.0                                                 0.
   2  30   29.6     387.0                                             29631.
   5   0   29.0     462.0                                             88930.
   7  30   28.4     396.0   4.1 17.1  0.8  2.0 16.2 11.78  4.40       88930.
  10   0   27.9     376.0                                             74096.
  12  30   27.1     431.0                                            118525.
  15   0   26.5     392.0                                             88930.
  17  30   25.8     545.0   7.5 13.4  1.0  2.2 31.1  7.63  4.40      103728.
  20   0   25.0     514.0                                            118561.
  22  30   24.3     463.0                                            103728.
  25   0   23.6     518.0                                            103728.
  27  30   22.9     690.0  10.8 10.1  0.6  2.1 39.8  5.07  4.40      133764.
  30   0   21.8     736.0                                            162990.
  32  30   21.0     710.0                                            118561.
  35   0   20.1     700.0   9.4 11.5  0.4  1.6 39.2  7.22  4.40      133359.
  37  30   19.3     708.0                                            118561.
  40   0   18.4     691.0                                            133395.
  42  30   17.5     685.0                                            133359.
  45   0   16.7     711.0                                            118561.
  46   9   16.5     720.0   9.1 12.0  0.2  1.7 36.7  7.49  4.40       64416.
  47  30   16.0     724.0                                            137215.
  50   0   15.1     661.0                                            133359.
  52  30   14.3     632.0                                            118561.
  55   0   13.4     630.0   7.1 13.8  0.8  1.9 29.2  8.41  4.40      133395.
  57  30   12.7     699.0                                            103728.
  60   0   11.9     733.0                                            118561.
  62  30   11.1     656.0                                            118525.
  65   0   10.5     632.0   7.7 12.6  0.9  0.9 42.8  8.81  4.40       88930.
  67  30    9.9     639.0                                             88930.
  70   0    9.4     662.0                                             74096.
  72  30    8.8     641.0                                             88894.
  75   0    8.2     618.0                                             88930.
  77  30    7.6     596.0   6.7 14.0  0.8  1.4 35.5  9.29  4.40       88894.
                                 B-1
  80   0    7.2     582.0                                             59299.
  82  30    6.7     570.0                                             74096.
  85   0    6.2     568.0                                             74096.
  87  30    5.8     564.0                                             59263.
  90   0    5.4     554.0                                             59299.
  92  30    5.0     556.0                                             59263.
  95   0    4.6     550.0                                             59263.
  95  48    4.5     552.0   6.5 14.2  0.6  1.1 38.4 10.14  4.40       46355.

REMARKS

     AVERAGE HEAT RELEASED:    97841.4 BTU/HR

     AVERAGE HEAT OUTPUT  :    33164.2 BTU/HR

     AVERAGE EFFICIENCY   :       33.9 %

                    TEST BY TIM, GLENN, PHIL, & TOM
```

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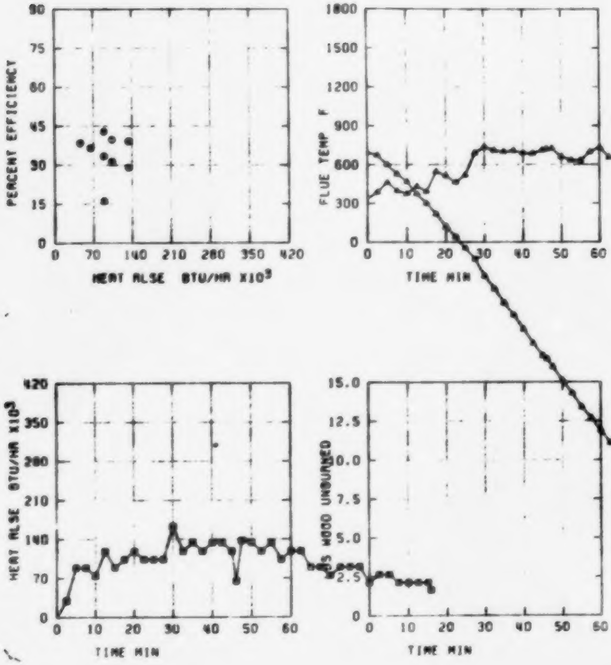
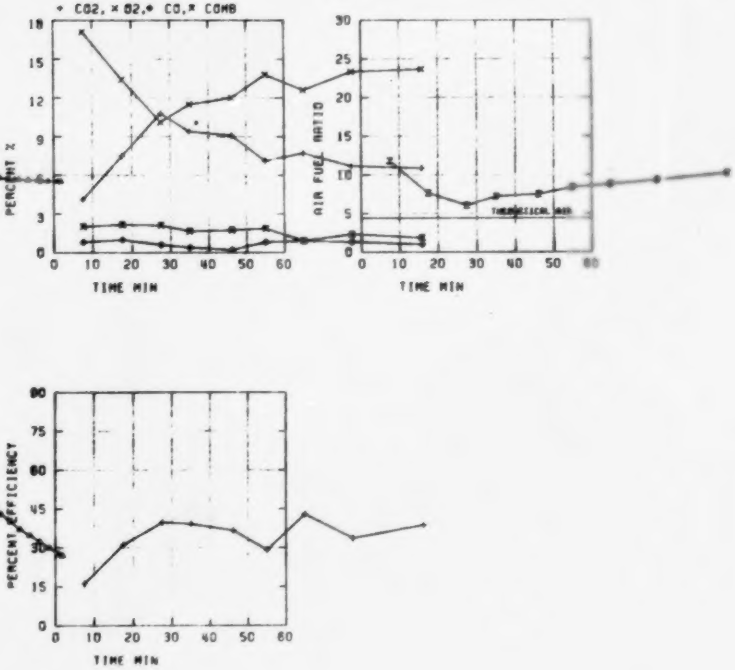
TEST NUMBER B-1

1-3/14/79



TEST NUMBER B-1

1-3/14/79



MICROFILMED FROM
BEST AVAILABLE COPY

WOOD BURNING TEST RESULTS

B-1 1a, 1b, 1c
NOx 2a, 2b, 2c
BIOMASS
EPA-5

TEST NUMBER : 2-3/14/79

DATE OF TEST : MARCH 14, 1979

AMBIENT TEMPERATURE : 77 DEG F

DAMPER SETTING :
ALL THREE INLETS OPEN TWO TURNS

FUEL : SPLIT RED OAK 4 PIECES

MOISTURE CONTENT 30.0 % HHV= -6174.7

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RLSE BTU/HR
0	0	29.7	600.0								0.
2	30	28.5	648.0	12.3	8.2	2.6	4.2	30.2	6.08	4.40	177324.
5	0	27.4	725.0								163027.
7	30	26.5	623.0								133359.
10	0	25.7	567.0								118561.
11	40	25.2	542.0	8.5	12.2	1.4	2.5	32.9	8.55	4.40	111145.
12	30	25.0	536.0								88894.
15	0	24.2	523.0								118561.
17	30	23.5	511.0								103728.
20	0	22.8	512.0								103728.
22	30	22.1	537.0	9.3	11.5	1.4	2.8	33.5	5.98	4.40	103728.
25	0	21.3	541.0								118561.
27	30	20.6	584.0								103728.
30	0	19.8	599.0								118561.
32	30	19.0	635.0	9.9	10.8	1.2	2.4	36.7	5.32	4.40	118561.
35	0	18.3	601.0								103728.
37	30	17.5	605.0								118561.
40	0	16.9	633.0								88930.
42	30	16.2	659.0	9.9	10.8	0.8	1.9	39.9	6.55	4.40	103728.
45	0	15.5	661.0								103728.
47	30	14.8	679.0								103728.
50	0	14.1	684.0								103728.
52	30	13.4	679.0	10.5	10.2	0.9	2.1	39.2	5.08	4.40	103764.
55	0	12.7	682.0								103728.
57	30	11.9	633.0								118561.
60	0	11.2	629.0								103728.
62	30	10.5	673.0								103728.
65	0	9.3	614.0	9.3	11.2	1.4	2.2	36.0	6.35	4.40	103728.
67	30	9.2	620.0								88930.
70	0	8.5	644.0								103728.
72	30	7.9	654.0								88930.
75	0	7.3	662.0	10.5	9.9	1.3	2.0	39.8	5.42	4.40	88894.
77	30	6.7	649.0								88930.

B-1

80	0	6.1	645.0								88894.
82	30	5.4	645.0								103764.
85	0	4.8	641.0								88894.
87	30	4.3	665.0	11.1	9.2	1.2	1.8	43.8	5.05	4.40	74396.
90	0	3.8	681.0								74396.
92	30	3.3	663.0								74396.
95	0	2.9	652.0								59299.
97	30	2.5	639.0								59263.
100	0	2.0	634.0								74396.
102	30	1.7	627.0								44465.
105	0	1.3	619.0	8.9	11.6	0.8	1.3	43.1	7.53	4.40	59263.

REMARKS

AVERAGE HEAT RELEASED: 100206.1 BTU/HR

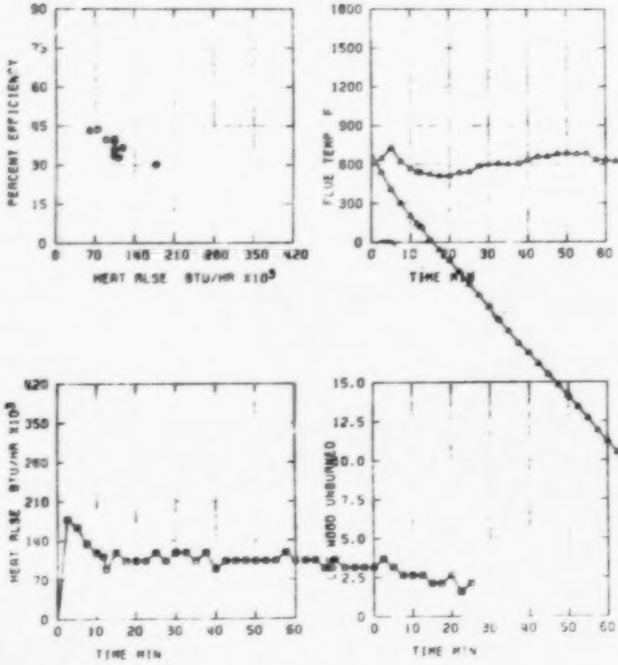
AVERAGE HEAT OUTPUT : 37276.2 BTU/HR

AVERAGE EFFICIENCY : 37.2 %

TEST BY TIM, GLENN, PHIL, & TOM

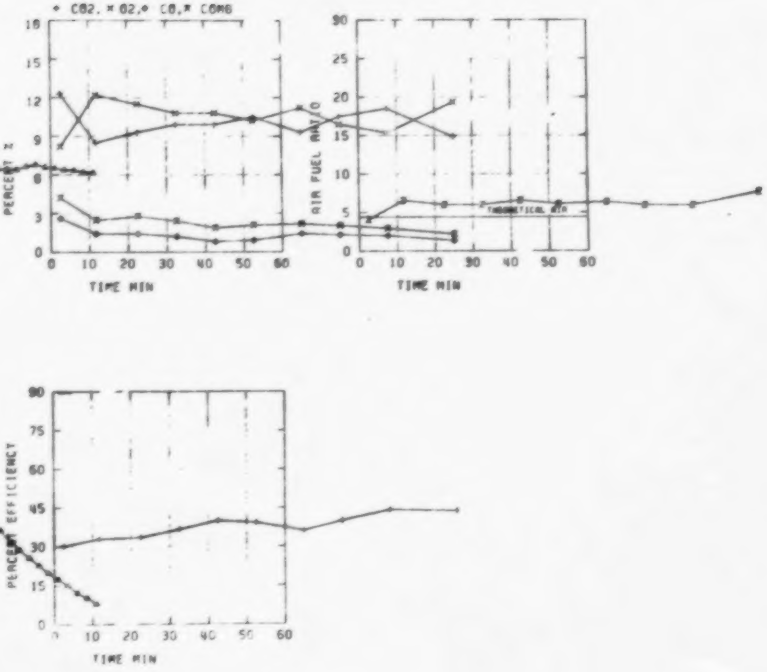
TEST NUMBER

2-3/14/79 B-1



TEST NUMBER B-1

2-3/14/79

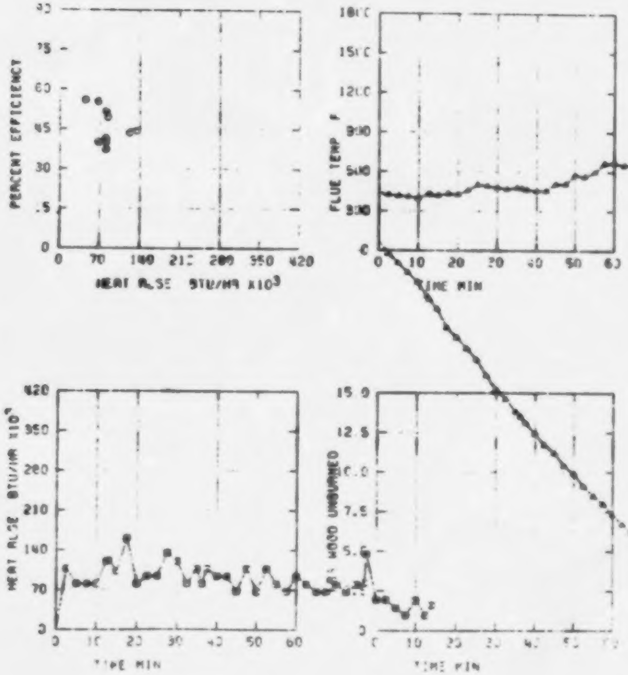


B-2
NOx
BIOMASS
EPA-5 (1½)
FROM SCREEN

```
                    WOOD BURNING TEST RESULTS

TEST NUMBER   :  1-3/21/79

DATE OF TEST  :  MARCH 21, 1979

AMBIENT TEMPERATURE :     81  DEG F

DAMPER SETTING :
                 BOTTOM OPEN TWO TURNS, TOP OPEN ONE TURN

FUEL :  WET OAK

MOISTURE CONTENT  35.0 %          HHV=   -5590.0


  TIME  LBS WOOD FLUE GAS %CO2  %O2  %CO %COM %EFF  A/F   THEO HEAT RLSE
                 TEMP (F)                          RATIO  A/F   BTU/HR

   0  0   24.6    437.0                                            0.
   2 30   23.8    424.0                                       107335.
   5  0   23.2    417.0   5.8 14.2  1.0  0.2 51.6 11.32  4.10   83476.
   7 30   22.6    410.0                                        80509.
  10  0   22.0    399.0                                        80509.
  12 30   21.1    429.0                                       120731.
 [illegible]      20.9    426.0   7.8 12.5  1.1  1.2 43.5  7.69  4.10  121934.
  15  0   20.3    420.0                                       103217.
  17 30   19.1    431.0                                       160985.
  20  0   18.5    425.0   8.4 12.1  1.3  1.5 37.2  6.57  4.10   80509.
  22 30   17.8    457.0                                        93905.
  25  0   17.1    501.0                                        93905.
  27 30   16.1    491.0  10.5  9.7  1.3  1.6 44.2  5.73  4.10  134160.
  30  0   15.2    490.0                                       120731.
  32 30   14.6    471.0                                        80509.
  35  0   13.9    480.0                                       107335.
  36 15   13.5    475.0   9.9 10.2  1.7  1.9 49.3  5.67  4.10   80509.
  37 30   13.1    464.0                                       107302.
  40  0   12.4    455.0                                        93905.
  42 30   11.7    455.0                                        93905.
  45  0   11.1    507.0   9.8 10.4  1.5  1.8 40.0  5.35  4.10   67080.
  47 30   10.4    506.0                                       107335.
  50  0    9.9    577.0                                        67080.
  52 30    9.1    564.0                                       107335.
  55  0    8.5    598.0  11.6  8.5  1.5  1.8 41.5  5.12  4.10   80509.
  57 30    8.0    566.0                                        67080.
  60  0    7.2    670.0                                        93905.
  62 30    6.7    651.0                                        80476.
  65  0    6.2    659.0  12.1  8.0  0.4  0.4 55.4  6.11  4.10   67080.
  67 30    5.7    665.0                                        67080.
  70  0    5.1    645.0                                        80509.
  72 30    4.6    625.0                                        67080.
  75  0    4.0    607.0                                        80509.

  77       3.5    598.0  10.3 10.2  0.7  0.7 69.4  6.34  4.10   93850.
  77 30    3.3    594.0                                       134127.
  80  0    2.8    565.0                                        53651.
  82 30    2.5    555.0                                        52684.
  85  0    2.2    545.0                                        40222.
  87 30    2.0    551.0                                        26858.
  90  0    1.6    544.0                                        53651.
  92 30    1.4    532.0                                        26825.
  9[illegible]  0    1.2    533.0   7.1 12.7  0.3  0.0 56.0 13.43  4.10   66735.

REMARKS

     AVERAGE HEAT RELEASED :   87493.7 BTU/HR

     AVERAGE HEAT OUTPUT   :   37572.3 BTU/HR

     AVERAGE EFFICIENCY    :      45.0 %

                    TEST CONDUCTED BY MIKE,TOM,GLENN,PHIL
```

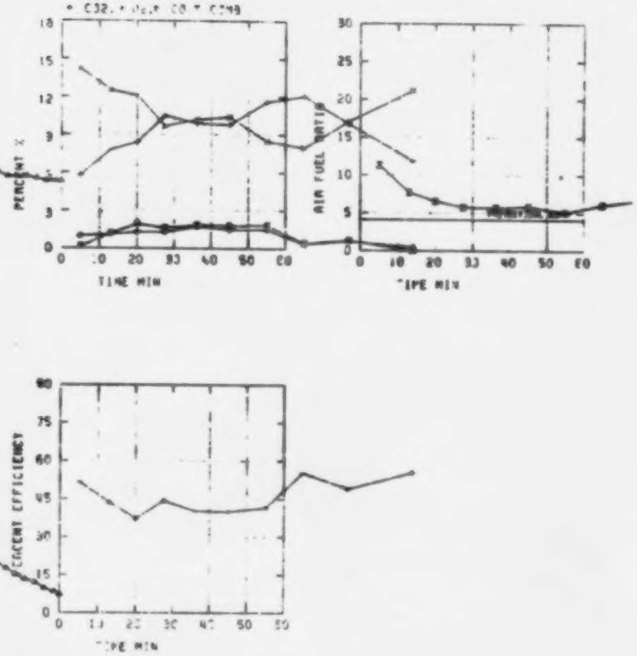
TEST NUMBER B-2

1-3/21/79



TEST NUMBER B-2

1-3/21/79



WOOD BURNING TEST RESULTS

B-3
NOx 1a, 1b, 1c
BIOSRBS
POM SCREEN

TEST NUMBER : 1-3/19/79

DATE OF TEST : MARCH 19,1979

AMBIENT TEMPERATURE : 76 DEG F

DAMPER SETTING :
BOTTOM FULL OPEN , TOP OPEN ONE TURN

FUEL : SEASONED PINE

MOISTURE CONTENT 25.0 % HHV= -6450.0

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RLSE BTU/HR
0	0	20.1	527.0								0.
2	30	19.2	753.0	10.4	8.9	1.0	0.0	55.8	7.85	4.69	139305.
5	0	17.9	695.0								201248.
7	30	16.5	701.0	15.0	3.4	3.3	1.4	50.0	4.47	4.69	216743.
10	0	15.1	720.0	15.1	3.2	3.7	1.7	47.1	4.25	4.69	216705.
12	30	13.6	701.0								232200.
13	45	13.1	694.0	15.3	3.0	3.9	2.0	46.1	[illegible]	4.69	154800.
15	0	12.4	693.0								216705.
17	30	11.2	688.0	15.2	3.1	3.5	1.5	49.7	4.35	4.69	185752.
20	0	10.1	707.0								170295.
22	30	9.0	729.0	14.9	3.6	3.1	1.3	49.9	4.57	4.69	170295.
25	0	7.9	704.0								170257.
26	49	7.0	720.0	14.5	4.2	2.9	1.4	49.3	4.70	4.69	191756.
27	30	6.7	720.0								169792.
30	0	5.7	727.0								154800.
31	28	5.0	695.0	14.7	3.6	3.6	1.5	48.3	4.42	4.69	184756.
32	30	4.7	725.0								112282.
35	0	3.7	693.0								154800.
37	30	3.0	727.0	14.0	4.7	1.8	0.0	60.5	5.73	4.69	108390.
40	0	2.4	729.0								92857.
42	30	1.4	706.0								154800.
45	0	0.9	716.0	12.0	6.7	0.9	0.0	60.3	5.78	4.69	77400.
47	30	0.5	713.0								61943.
50	0	0.0	675.0								77400.

REMARKS

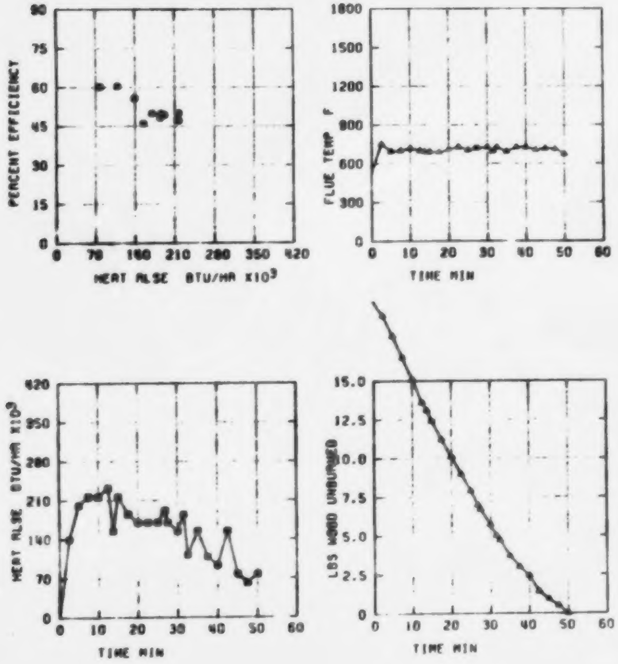
AVERAGE HEAT RELEASED: 155574.6 BTU/HR

AVERAGE HEAT OUTPUT : 80974.2 BTU/HR

AVERAGE EFFICIENCY : 52.0 %

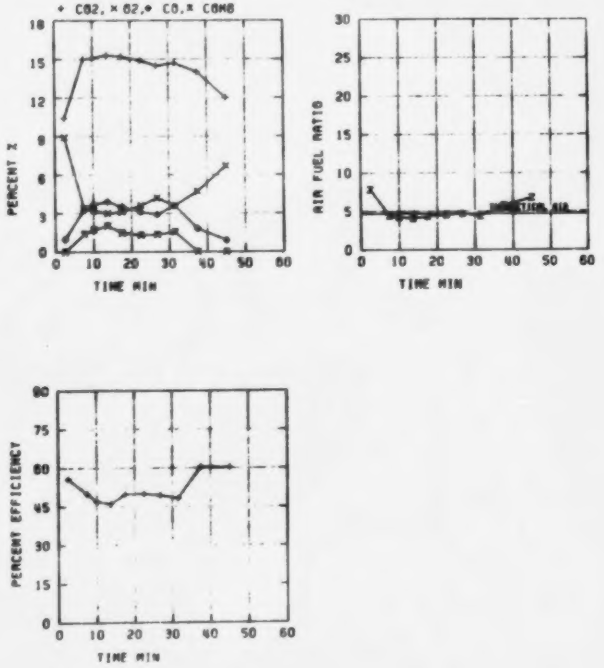
TEST NUMBER B-3

1-3/19/79



TEST NUMBER B-3

1-3/19/79



WOOD BURNING TEST RESULTS

B-3
NOx 2a, 2b, 2c
8 in SACS
EPA-5

TEST NUMBER : 2-3/19/79

DATE OF TEST : MARCH 19,1979

AMBIENT TEMPERATURE : 81 DEG F

DAMPER SETTING :
BOTTOM OPEN TWO TURNS, TOP OPEN ONE TURN

FUEL : SEASONED PINE

MOISTURE CONTENT 25.0 % HHV= -6450.0

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RLSE BTU/HR
0	0	20.6	437.0								0.
2	30	19.9	510.0								108390.
5	0	19.1	529.0	9.7	9.9	1.1	0.1	61.7	8.35	4.69	123810.
7	30	18.2	558.0								139343.
10	0	17.2	590.0	16.1	3.6	3.5	4.4	37.8	3.46	4.69	154800.
12	30	16.0	610.0								185752.
13	30	15.5	609.0	15.7	3.5	3.2	2.9	44.2	3.92	4.69	193500.
15	0	14.9	615.0								154825.
17	30	13.6	616.0	15.6	3.6	3.5	3.3	41.6	3.78	4.69	201210.
20	0	12.5	618.0								170295.
22	30	11.3	623.0	14.4	4.8	3.6	3.3	39.4	3.98	4.69	185752.
25	0	10.3	616.0								154800.
27	30	9.3	626.0	15.6	3.7	3.3	3.2	41.9	3.84	4.69	154800.
30	0	8.5	635.0								123848.
32	30	7.5	646.0	15.1	4.0	2.8	2.1	47.5	4.35	4.69	154800.
35	0	6.7	660.0								123848.
37	30	6.0	660.0								108352.
40	0	5.4	678.0	13.4	6.3	1.0	0.6	57.3	5.98	4.69	92895.
42	30	4.8	677.0								92857.
45	0	4.2	660.0								92895.

REMARKS

AVERAGE HEAT RELEASED: 141041.2 BTU/HR

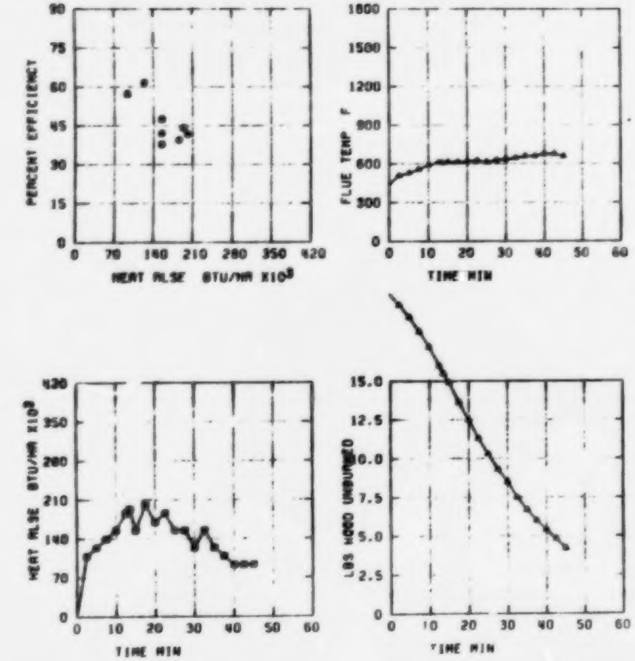
AVERAGE HEAT OUTPUT : 66942.2 BTU/HR

AVERAGE EFFICIENCY : 47.5 %

TEST BY TOM, PHIL, AND MIKE

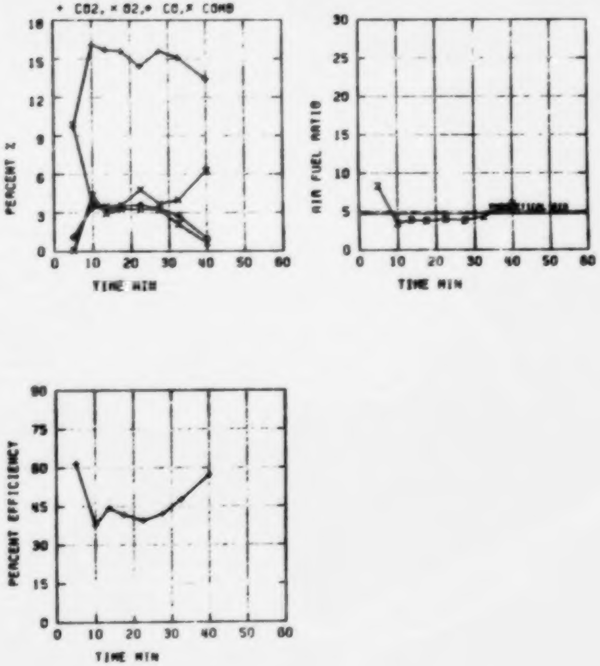
TEST NUMBER B-3

2-3/19/79



TEST NUMBER B-3

2-3/19/79



WOOD BURNING TEST RESULTS

B-4
NOx 1a, 1b, 1c
BIOMASS
EPA-5 (1&2)
POM SCREEN

TEST NUMBER : 1-3/15/79

DATE OF TEST : MARCH 15,1979

AMBIENT TEMPERATURE : 71 DEG F

DAMPER SETTING :
TOP-1 TURN, BOTTOM-FULL OPEN

FUEL : SPLIT 'GREEN' PINE

MOISTURE CONTENT 30.0 % HHV= -6174.7

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RLSE BTU/HR
0	0	13.2	553.0								0.
2	30	12.4	459.0	5.1	15.0	1.1	0.4	45.6	12.75	4.40	118561.
5	0	11.4	460.0								148193.
7	30	10.6	304.0	3.1	17.1	0.6	0.0	55.4	22.71	4.40	118561.
10	0	9.7	291.0								133359.
12	30	8.9	487.0	7.6	12.8	1.3	1.6	39.4	7.83	4.40	118561.
15	0	7.8	573.0								162990.
17	30	6.6	632.0	10.9	9.9	1.3	2.9	35.4	5.35	4.40	177860.
20	0	5.4	728.0								177824.
22	30	4.2	753.0	12.9	6.4	1.6	0.6	54.2	5.58	4.40	177824.
25	0	3.1	783.0								163027.
27	30	2.2	801.0	14.1	5.8	0.4	0.3	59.3	5.74	4.40	133359.
30	0	1.2	802.0								148193.
32	30	0.8	790.0	11.9	8.3	0.3	0.5	54.8	6.68	4.40	59263.
35	0	0.3	732.0								74096.
37	30	0.0	702.0	9.4	10.0	0.5	0.0	57.7	8.37	4.40	44465.

REMARKS

AVERAGE HEAT RELEASED: 130409.0 BTU/HR

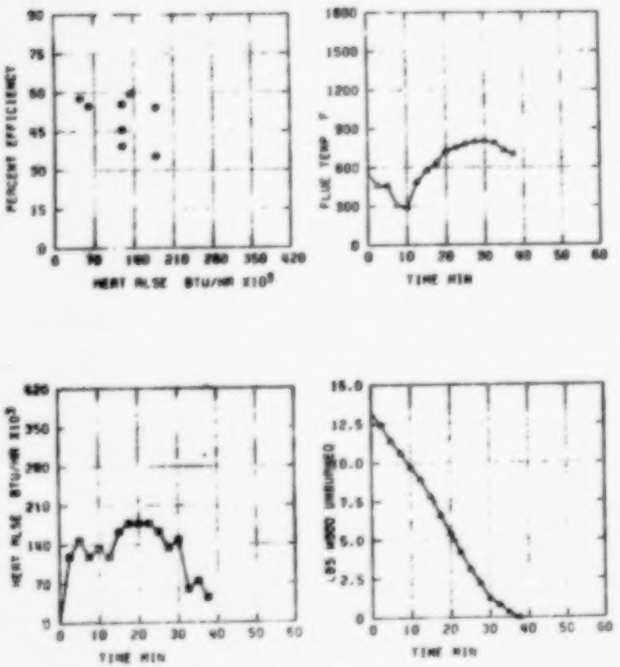
AVERAGE HEAT OUTPUT : 63249.0 BTU/HR

AVERAGE EFFICIENCY : 48.5 %

TEST CONDUCTED BY TOM PRUITT AND PHIL MAULDIN

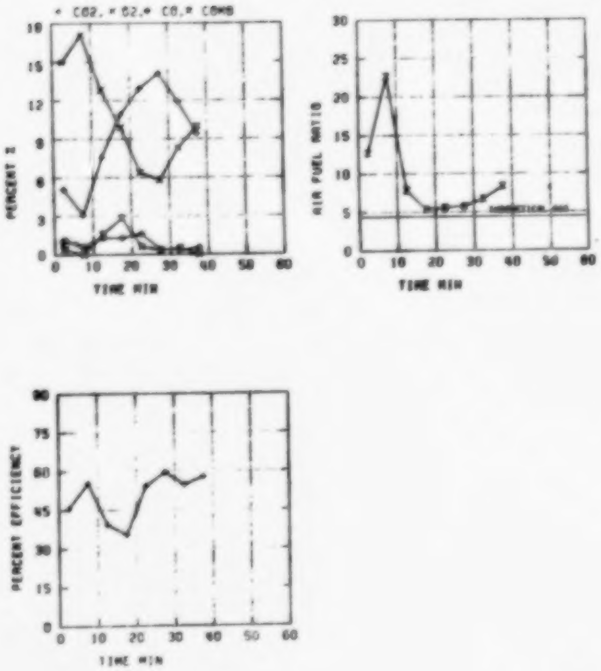
TEST NUMBER B-9

1-3/15/79



TEST NUMBER B-9

1-3/15/79



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                    WOOD BURNING TEST RESULTS

TEST NUMBER    :  1-3/16/79

DATE OF TEST   :  MARCH 16, 1979

AMBIENT TEMPERATURE :      70  DEG F

DAMPER SETTING :
                    TOP-1 TURN, BOTTOM-FULL OPEN

FUEL :  SPLIT 'GREEN' PINE

MOISTURE CONTENT  30.0 %           HHV=   -6174.7


 TIME  LBS WOOD FLUE GAS %CO2  %O2   %CO  %COM %EFF   A/F   THEO HEAT RISE
                 TEMP (F)                               RATIO   AIR   BTU/HR

  0   0    19.0     486.0                                                 0.
  2  30    18.2     486.0                                            118561.
  5   0    17.5     467.0   5.2 15.3  1.0   1.1 35.0 11.44  4.40  103728.
  7  30    16.1     584.0  10.6  9.5  1.4   1.5 46.2  5.06  4.40  207455.
 10   0    14.7     570.0                                            207492.
 12  30    13.4     602.0  10.3  9.8  1.0   1.0 50.9  5.80  4.40  192622.
 15   0    12.2     574.0   9.9 10.7  2.0   3.3 30.7  5.25  4.40  177860.
 17  30    11.1     593.0                                            162990.
 20   0    10.0     672.0  11.9  8.4  1.6   2.4 40.1  5.10  4.40  163027.
 22  30     9.0     724.0                                            148193.
 25   0     8.1     745.0  12.5  7.9  0.9   1.8 45.1  5.44  4.40  133359.
 27  30     7.3     737.0                                            118561.
 30   0     6.6     781.0  12.7  8.3  0.3   2.2 42.1  5.41  4.40  103728.
 32  30     5.9     790.0                                            103728.
 35   0     5.1     802.0                                            118561.
 37  30     4.3     858.0  14.0  5.8  0.8   0.7 55.8  5.46  4.40  118561.
 40   0     3.7     821.0                                             88930.
 42  30     3.1     762.0                                             88894.
 45   0     2.9     701.0   7.6 12.8  0.3   0.3 49.0 10.37  4.40   44465.
 47  30     2.4     646.0                                             59263.
 50   0     2.2     591.0                                             29608.
 52  30     1.9     571.0                                             44429.
 55   0     1.7     528.0                                             29608.
 60   0     1.2     502.0   5.2 15.4  0.4   0.5 44.5 13.90  4.40   37048.

REMARKS

     AVERAGE HEAT RELEASED:  109909.8 BTU/HR

     AVERAGE HEAT OUTPUT  :    47926.5 BTU/HR

     AVERAGE EFFICIENCY   :        43.6 %
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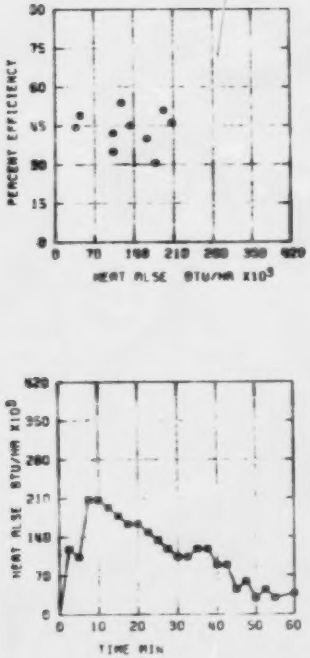
B-4

NOx 24,26,2C

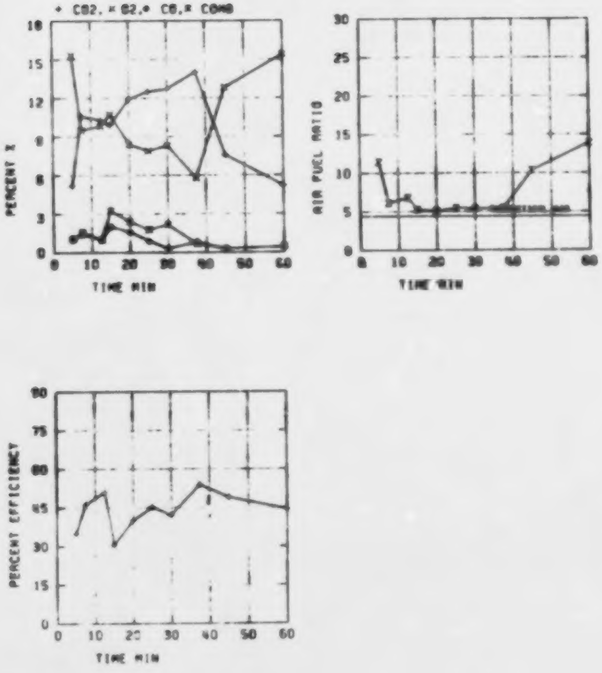
TEST NUMBER B-4

1-3/16/79



TEST NUMBER B-4

1-3/16/79



WOOD BURNING TEST RESULTS C-1

NO_x
[illegible]

TEST NUMBER : 1-4/04/79

DATE OF TEST : APRIL 4, 1979

AMBIENT TEMPERATURE : 81 DEG F

DAMPER SETTING :
1.5 TURNS OPEN

FUEL : SEASONED RED OAK

MOISTURE CONTENT 30.0 % MHV= -6174.7

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RELSE BTU/HR
0	0	25.7	331.0								0.
2	30	24.9	547.0	13.4	6.4	2.2	2.4	46.0	4.49	4.40	118561.
5	0	23.9	573.0								148193.
7	30	22.7	549.0								177824.
10	0	21.6	551.0	16.0	2.4	4.2	2.7	46.9	3.50	4.40	162990.
12	30	20.3	569.0								192656.
15	0	19.0	563.0	15.6	4.0	3.0	3.4	43.2	3.60	4.40	192656.
17	30	17.8	554.0	15.4	4.4	3.2	4.1	39.7	3.45	4.40	177824.
20	0	16.7	567.0								163027.
22	30	15.6	597.0								162990.
25	0	14.0	607.0	15.0	4.6	2.8	3.1	43.3	3.83	4.40	148193.
27	30	13.3	595.0								192656.
30	0	12.1	594.0	15.4	4.2	3.8	4.5	36.6	3.27	4.40	177824.
32	30	11.0	588.0								163027.
35	0	10.0	604.0	14.2	5.2	3.0	2.8	45.0	4.00	4.40	148193.
37	30	9.0	630.0								148193.
40	0	8.2	653.0								118561.
42	30	7.5	668.0	14.6	4.6	2.2	1.4	52.0	4.54	4.40	103728.
45	0	6.7	703.0								118561.
47	30	6.0	776.0								103728.
50	0	5.3	772.0								103728.
52	30	4.7	798.0	15.0	5.0	2.0	2.8	41.1	4.08	4.40	88930.
55	0	4.1	746.0								40894.
57	30	3.5	573.0								88930.
60	0	2.9	481.0								88930.
62	30	2.5	439.0								59263.
65	0	2.2	403.0	6.6	14.0	1.8	2.5	28.3	7.37	4.40	44465.

REMARKS

AVERAGE HEAT RELEASED: 133943.3 BTU/HR

AVERAGE HEAT OUTPUT : 57661.3 BTU/HR

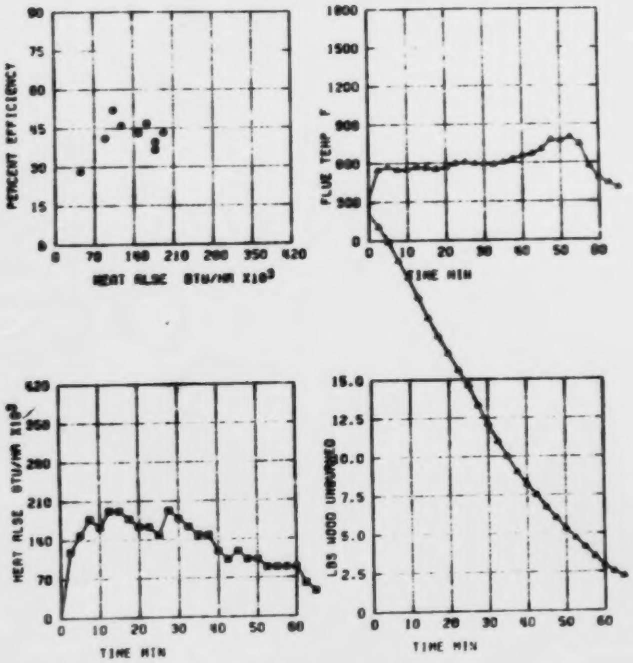
C-1

AVERAGE EFFICIENCY : 43.1 %

TEST CONDUCTED BY DEBBIE & JAGER

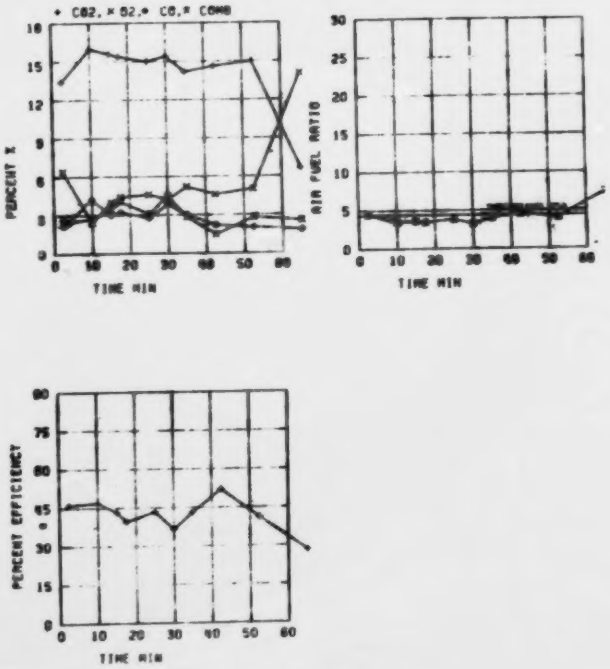
TEST NUMBER C-1

1-4/04/79



TEST NUMBER C-1

1-4/04/79



WOOD BURNING TEST RESULTS C-2

NOx 1a, 1b, 1c
POM [illegible]

TEST NUMBER : 1-3/29/79

DATE OF TEST : MARCH 29.1979 12:00 PM

AMBIENT TEMPERATURE : 82 DEG F

DAMPER SETTING :
TWO AND ONE-HALF TURNS OPEN

FUEL : GREEN OAK(SPLIT)

MOISTURE CONTENT 33.0 %   HHV= -5910.1

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RISE BTU/HR
0	0	28.8	453.0								0.
2	30	27.9	400.0								127678.
5	0	27.1	350.0	3.8	17.2	0.7	1.5	23.1	13.29	4.22	113446.
7	30	26.4	398.0								99317.
10	0	25.5	408.0								127644.
12	30	24.5	492.0	3.1	17.4	0.5	0.1	33.7	21.94	4.22	141842.
15	0	23.2	492.0								184401.
17	30	22.0	528.0								170203.
18	30	21.6	537.0	7.8	12.4	1.1	1.0	44.7	8.13	4.22	141807.
20	0	20.8	534.0								169134.
22	30	19.5	542.0								184401.
25	0	18.3	562.0	8.0	12.1	1.3	1.1	42.9	7.70	4.22	170203.
27	30	17.0	540.0								198401.
30	0	15.7	557.0	7.6	12.2	1.3	0.4	49.6	8.60	4.22	184401.
32	30	14.6	583.0								150005.
35	0	13.5	575.0								156040.
37	30	12.6	586.0	2.5	13.0	1.1	1.5	55.2	7.82	4.22	127644.
40	0	11.6	589.0								141842.
42	30	10.7	586.0								127678.
45	0	9.9	621.0	7.5	13.0	0.4	0.6	46.4	9.52	4.22	113480.
47	30	9.1	628.0								113446.
50	0	8.5	612.0								85119.
52	30	7.8	588.0								99282.
55	0	7.3	563.0	7.9	13.8	0.3	2.9	24.7	6.98	4.22	70921.
57	30	6.7	599.0								85119.
60	0	6.1	610.0								85084.
62	30	5.6	622.0								70921.
65	0	5.0	635.0								85119.
67	30	4.6	612.0								56723.
70	0	4.1	582.0	6.0	14.7	0.6	1.0	34.0	10.47	4.22	70921.
72	30	3.7	775.0								56757.
75	0	3.2	660.0								70921.
77	30	2.8	645.0								56723.
						C-2					
80	0	2.4	830.0								56757.
82	30	1.9	582.0								70921.
85	0	1.5	567.0	4.7	16.2	0.5	1.1	24.0	12.03	4.22	56723.
87	30	1.2	535.0								42339.

REMARKS

AVERAGE HEAT RELEASED: 111852.5 BTU/HR

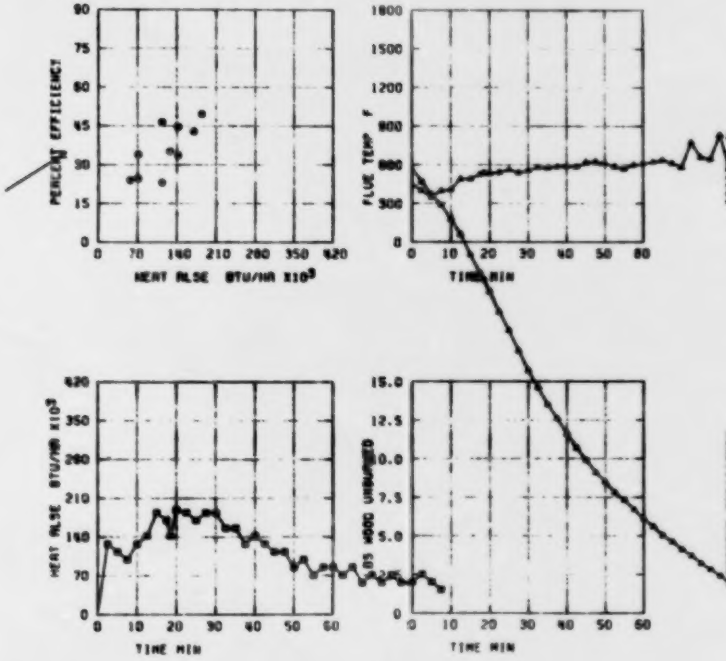
AVERAGE HEAT OUTPUT : 40823.0 BTU/HR

AVERAGE EFFICIENCY : 36.5 %

TEST CONDUCTED BY GLENN & MIKE

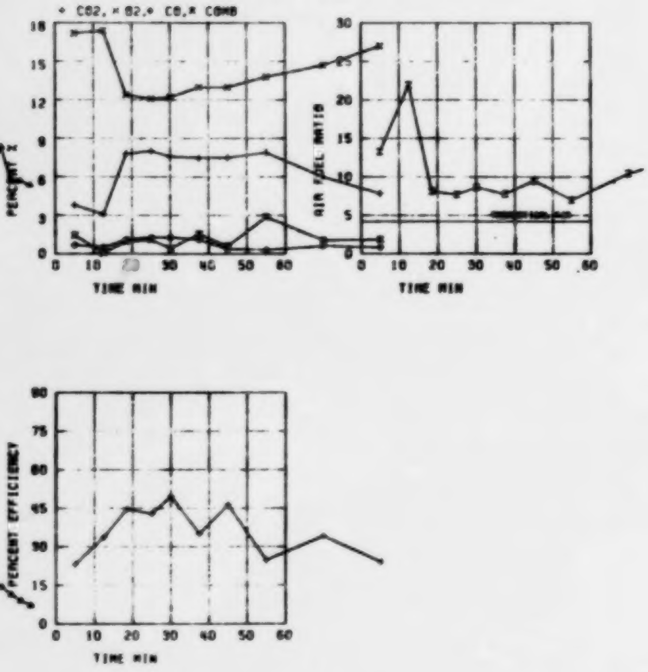
TEST NUMBER C-2

1-3/29/79



TEST NUMBER C-2

1-3/29/79



WOOD BURNING TEST RESULTS C-2

TEST NUMBER : 2-3/29/79

DATE OF TEST : MARCH 29, 1979

AMBIENT TEMPERATURE : 82 DEG F

DAMPER SETTING :
TWO TURNS EACH

FUEL : GREEN OAK(SPLIT)

MOISTURE CONTENT 33.0 % HHV= -5910.1

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RLSE BTU/HR
0	0	29.6	407.0								0.
2	30	29.2	416.0								56723.
5	0	28.6	453.0								85119.
7	30	28.0	459.0								85384.
10	0	27.3	467.0	7.1	13.5	1.0	1.5	38.1	8.22	4.22	99317.
12	30	26.5	525.0								113446.
15	0	25.7	504.0								113480.
17	30	25.0	551.0	8.0	12.4	1.2	1.5	38.5	7.38	4.22	99282.
20	0	24.1	567.0								127678.
22	30	23.3	657.0								113480.
25	0	22.4	636.0	7.0	13.4	1.0	1.1	35.4	8.74	4.22	127644.
27	30	21.4	635.0								141842.
30	0	20.6	648.0								113480.
32	30	19.6	697.0	6.4	19.0	0.8	10.6	-20.1	3.65	4.22	141842.
35	0	18.8	708.0								113480.
37	30	17.9	739.0								127644.
40	0	16.9	829.0								141842.
42	30	15.9	858.0	6.8	13.5	0.7	0.5	32.1	10.11	4.22	141842.
45	0	14.8	862.0								156040.
47	30	13.8	854.0								141242.
50	0	12.9	949.0	6.9	13.0	0.9	1.2	20.1	8.89	4.22	127544.
52	30	12.0	970.0								127644.
55	0	11.1	1027.0								127678.
57	30	10.2	1110.0	7.0	13.6	0.4	0.7	17.7	9.93	4.22	127644.
60	0	9.3	1053.0								127678.
62	30	8.5	997.0								113446.
65	0	7.8	1020.0	6.9	13.9	0.2	0.8	20.3	10.15	4.22	99367.
67	30	7.2	942.0								85384.
70	0	6.6	882.0								85119.
72	30	6.1	869.0								70921.
75	0	5.6	875.0								70921.
77	30	5.1	887.0								70921.
80	0	4.7	882.0	6.2	14.4	0.2	0.3	29.7	12.05	4.22	56723.
82	30	4.2	839.0								70921.
85	0	3.8	725.0								56757.
87	30	3.5	655.0								70921.
90	0	3.1	633.0								28361.
92	30	2.9	649.0								28361.
95	0	2.6	661.0								42559.
97	30	2.4	644.0								28361.
100	0	2.1	628.0								42559.
102	30	1.8	573.0								42559.
105	0	1.7	583.0	3.0	16.7	0.3	0.0	26.2	23.65	4.22	14163.

C-2

REMARKS

AVERAGE HEAT RELEASED: 94222.9 BTU/HR

AVERAGE HEAT OUTPUT : 20581.8 BTU/HR

AVERAGE EFFICIENCY : 21.8 %

TEST CONDUCTED BY LES & MIKE

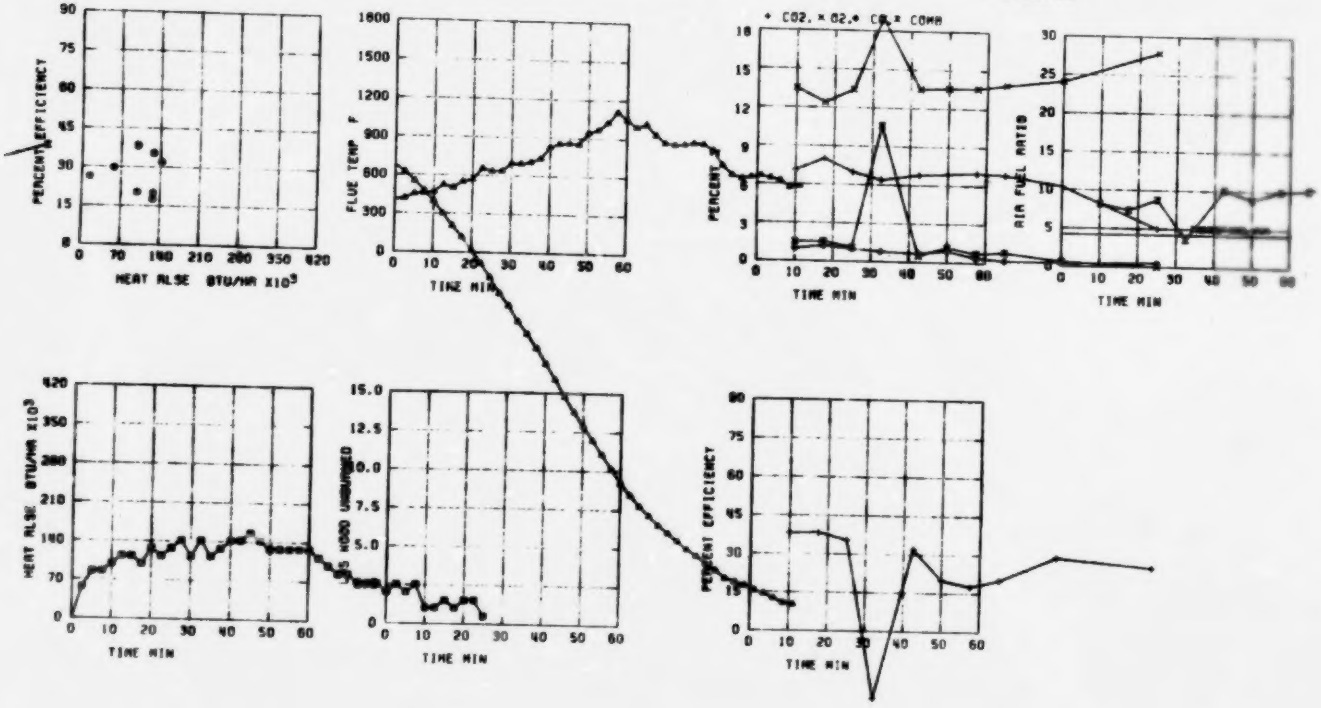
MICROFILMED FROM
BEST AVAILABLE COPY

TEST NUMBER C-2

2-3/29/79

TEST NUMBER C-2

2-3/29/79



WOOD BURNING TEST RESULTS C-2

TEST NUMBER : 1-4/03/79

DATE OF TEST : APRIL 3, 1979 1:50 PM

AMBIENT TEMPERATURE : 75 DEG F

DAMPER SETTING :
TWO TURNS EACH

FUEL : GREEN RED OAK

MOISTURE CONTENT 33.0 % HHV= -5910.1

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%CH4	%EFF	A/F RATIO	THEO AIR	HEAT RELS BTU/HR
0	0	20.2	489.0								0.
2	30	19.7	441.0								70921.
5	0	18.8	525.0	11.3	8.9	0.2	0.3	64.6	6.94	4.22	127644.
7	30	17.7	558.0								156043.
10	0	16.5	581.0	12.3	7.5	2.0	2.0	44.9	4.81	4.22	170203.
12	30	15.3	597.0	11.9	8.1	1.6	1.8	45.5	5.14	4.22	170203.
15	0	14.2	587.0								156043.
17	30	13.2	597.0	11.1	9.1	1.4	1.6	43.7	5.50	4.22	141842.
20	0	12.2	624.0								141842.
22	30	11.2	644.0	12.0	8.1	1.2	1.5	47.5	5.41	4.22	141842.
25	0	10.3	645.0								127644.
27	30	9.4	645.0	11.5,	8.3	1.0	0.6	55.3	6.19	4.22	127678.
30	0	8.5	646.0								127644.
32	30	7.6	663.0								127644.
35	0	6.8	680.0	12.0	8.2	1.2	1.7	44.8	5.31	4.22	113480.
37	30	6.0	690.0								113480.
40	0	5.3	701.0	11.4	8.9	0.9	1.4	45.6	5.81	4.22	99282.
42	30	4.7	635.0								85119.
45	0	4.1	586.0								85084.
47	30	3.7	618.0								56757.
50	0	3.2	634.0	8.5	12.2	0.3	1.0	44.6	8.20	4.22	70921.
52	30	2.7	695.0								70921.
55	0	2.3	674.0								56725.
62	30	1.0	607.0	7.5	13.5	0.1	1.2	39.7	9.12	4.22	61467.

REMARKS

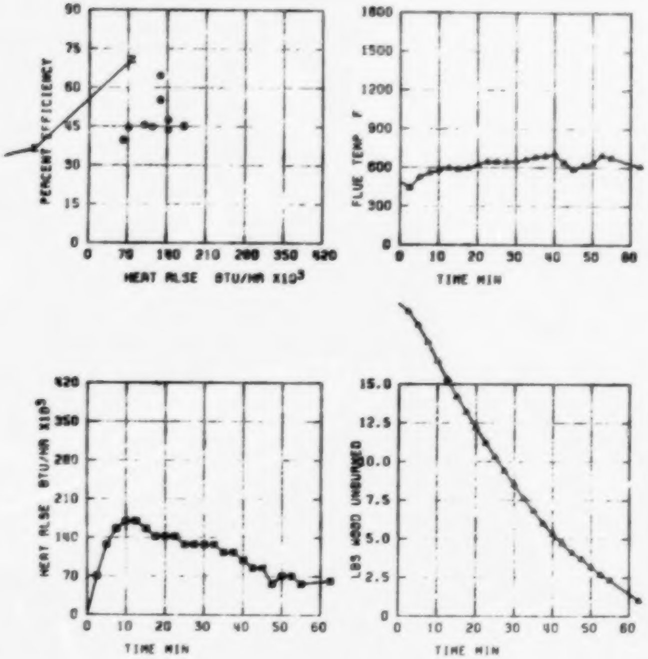
AVERAGE HEAT RELEASED: 108934.0 BTU/HR

AVERAGE HEAT OUTPUT : 52639.5 BTU/HR

AVERAGE EFFICIENCY : 48.3 %

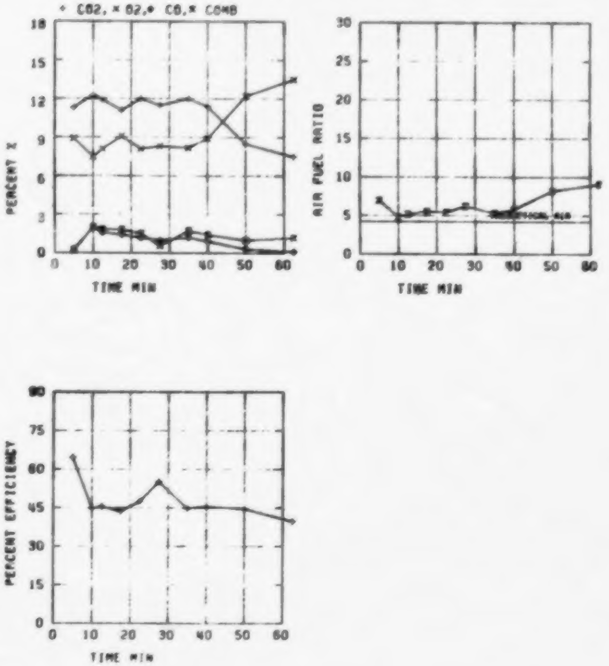
TEST NUMBER C-2

I-4/03/79



TEST NUMBER C-2

I-4/03/79



WOOD BURNING TEST RESULTS C-3

NOx
POM Screen
SOx
EPA5
POM
Bags

TEST NUMBER : 2-3/28/79

DATE OF TEST : MARCH 28, 1979

AMBIENT TEMPERATURE : 77 DEG F

DAMPER SETTING :
ONE TURN EACH

FUEL : SEASONED PINE

MOISTURE CONTENT 30.0 % HHV= -6174.7

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%CUM	%EFF	A/F RATIO	THEO AIR	HEAT RLSE BTU/HR
0	0	23.8	366.0								0.
2	30	23.4	412.0								59299.
5	0	22.9	478.0								74390.
5	30	22.6	492.0	10.0	10.0	1.4	1.3	50.1	6.54	4.40	222325.
7	30	22.0	503.0								111117.
10	0	21.0	529.0								148193.
12	0	20.2	534.0	13.0	6.4	2.4	1.9	49.3	4.74	4.40	148202.
12	40	19.9	540.0								222325.
15	0	18.9	563.0								148193.
17	30	17.8	569.0	13.0	6.4	2.6	2.1	46.3	4.59	4.40	162990.
20	0	16.7	575.0								165327.
22	30	15.8	594.0								133355.
23	30	15.5	608.0	13.4	6.0	2.2	1.7	49.4	4.77	4.40	111163.
25	0	15.0	630.0								123494.
27	30	14.2	673.0								116501.
30	0	13.2	685.0								143193.
33	20	13.0	681.0	12.0	7.2	2.2	1.1	49.6	5.45	4.40	222235.
32	30	12.2	675.0								136802.
35	0	11.4	679.0								116561.
37	0	10.7	691.0	13.2	5.6	2.8	1.2	49.5	4.80	4.40	125660.
37	30	10.6	697.0								74165.
40	0	9.7	705.0								133359.
42	30	9.2	746.0								74696.
45	0	8.7	905.0								74386.
46	0	8.3	876.0	12.0	7.6	1.2	0.5	49.9	6.15	4.40	148157.
47	30	7.8	862.0								123494.
50	0	7.2	866.0								66330.
52	30	6.3	799.0								133329.
55	0	6.2	791.0								14634.
57	30	6.0	798.0	11.2	8.8	3.4	0.1	50.6	7.27	4.40	29631.
60	0	5.2	752.0								118561.
62	30	4.5	705.0								133720.
65	0	4.0	656.0								74390.
						C-3					
66	30	3.6	614.0	8.8	13.6	0.6	4.6	14.7	3.46	4.40	56831.
67	30	3.5	613.0								30394.
70	0	3.4	637.0								14834.
72	30	3.3	663.0								14790.
75	0	3.0	642.0								44605.
77	30	2.4	592.0								88950.
80	0	1.9	504.0								74690.
82	30	1.7	489.0								27031.
85	0	1.5	485.0	7.2	12.8	3.2	0.0	63.5	11.32	4.40	29631.

REMARKS

AVERAGE HEAT RELEASED: 97197.1 BTU/HR

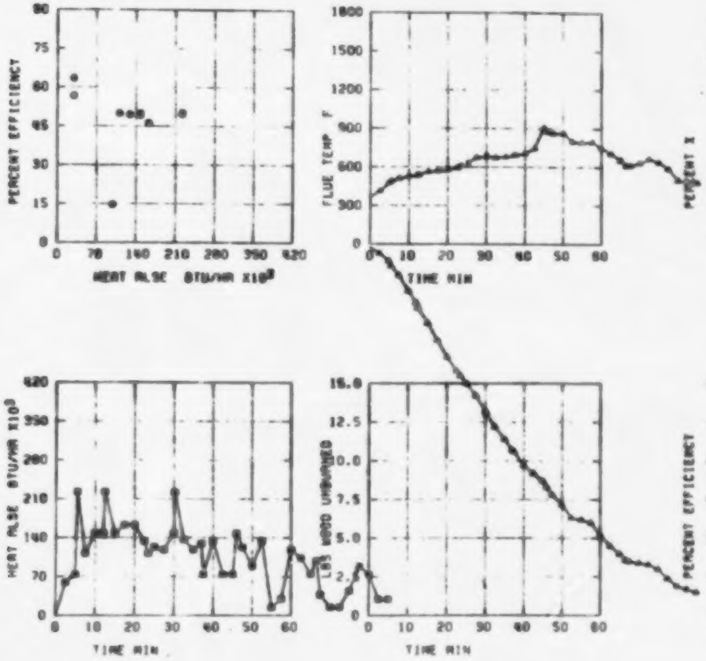
AVERAGE HEAT OUTPUT : 45981.1 BTU/HR

AVERAGE EFFICIENCY : 47.3 %

TEST CONDUCTED BY JAGER, DEBOIL, & TYLER

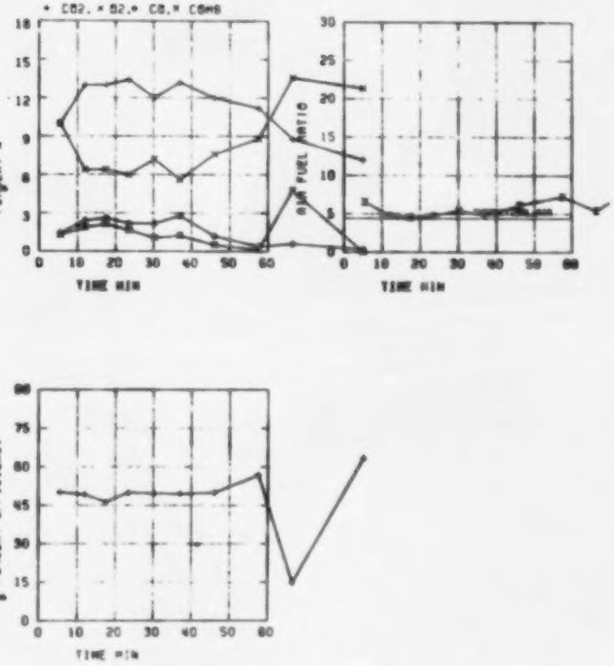
TEST NUMBER C-3

2-3/28/79



TEST NUMBER C-3

2-3/28/79



101

WOOD BURNING TEST RESULTS C-4

NOx 1a, 1b, 1c

EPA-5

TEST NUMBER : 1-3/22/79

DATE OF TEST : MARCH 22, 1979

AMBIENT TEMPERATURE : 78 DEG F

DAMPER SETTING :
BOTH DAMPERS TWO AND ONE HALF TURNS OPEN

FUEL : WET PINE

MOISTURE CONTENT 30.0 % HHV= -6020.0

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RLSE BTU/HR
0	0	20.0	380.0								0.
2	30	19.2	351.0								115556.
5	55	19.0	339.0	4.7	15.7	1.4	1.3	31.3	11.10	4.40	21164.
5	0	18.4	337.0								-236304.
7	30	18.0	346.0								57813.
10	0	17.4	375.0								86667.
12	0	16.9	388.0	6.4	14.0	1.4	1.0	35.7	8.77	4.40	90300.
12	30	16.8	386.0								72311.
15	0	16.3	379.0								115591.
17	30	15.1	384.0	6.5	13.7	1.3	1.1	45.0	9.38	4.40	130018.
20	0	14.6	429.0								72240.
22	30	13.9	476.0								101129.
25	0	12.7	500.0	8.8	11.4	2.2	2.0	31.4	5.93	4.40	175569.
27	30	11.8	546.0								130353.
29	15	11.0	530.0	8.9	11.4	2.0	2.5	31.4	6.01	4.40	165130.
30	0	10.7	560.0								144386.
32	30	10.0	603.0								101164.
35	0	8.9	655.0	10.9	9.0	1.9	1.9	39.1	5.57	4.40	158937.
37	30	8.1	702.0								115591.
40	0	7.1	821.0	13.1	6.5	1.6	1.5	42.9	5.05	4.40	144480.
45	0	5.3	1056.0								130356.
46	5	4.9	1054.0	16.8	3.1	2.7	3.8	30.8	3.39	4.40	133334.
47	30	4.3	1031.0								153034.
50	0	3.3	923.0								144480.
51	0	3.0	884.0	13.0	7.1	0.1	0.2	54.7	6.43	4.40	103376.
52	30	2.3	826.0								108540.
55	0	1.9	775.0								57778.
57	30	1.3	716.0								66702.
59	0	1.0	699.0	9.4	10.8	0.3	0.1	54.5	8.66	4.40	72252.
60	0	1.0	708.0								0.
62	30	0.8	682.0								20889.

REMARKS C-4

AVERAGE HEAT RELEASED: 110960.3 BTU/HR

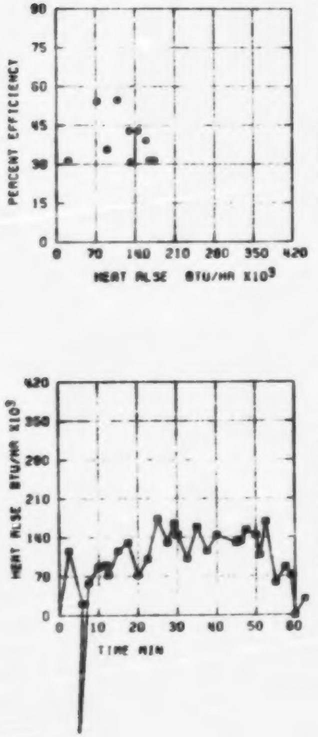
AVERAGE HEAT OUTPUT : 43328.0 BTU/HR

AVERAGE EFFICIENCY : 38.8 %

TEST CONDUCTED BY MIKE, BURT, GLENN

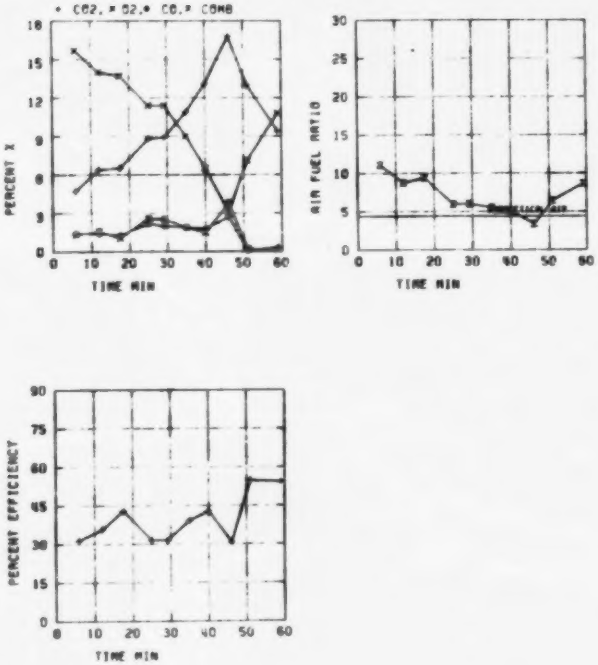
TEST NUMBER

1-3/22/79



TEST NUMBER

1-3/22/79



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BEST AVAILABLE COPY

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WOOD BURNING TEST RESULTS C-4

TEST NUMBER    :  1-3/23/79

DATE OF TEST  :  MARCH 23, 1979

AMBIENT TEMPERATURE :     72  DEG F

DAMPER SETTING :
                    BOTH DAMPERS OPEN THREE TURNS

FUEL :  WET PINE

MOISTURE CONTENT  30.0 %          HHV=   -6020.0


 TIME   LBS WOOD FLUE GAS %CO2   %O2   %CO  %CO4 %EFF  A/F    THEO HEAT RISE
                 TEMP (F)                                RATIO   AIR   BTU/HR

  0   0    14.1     402.0                                                  0.
  2  30    13.3     436.0                                             115391.
  4  30    12.7     533.0   8.4 11.6   1.3   0.7 45.0   7.05   4.40  108376.
  5   0    12.3     510.0                                             286389.
  7  30    11.7     558.0   9.9 10.0   1.0   1.3 44.4   6.44   4.40   86702.
 10   0    10.6     643.0                                             158907.
 10  45    10.0     647.0  10.7  9.1   1.8   1.5 41.9   5.88   4.40  289007.
 12  30     9.5     705.0                                             103200.
 13  30     9.0     772.0  12.9  6.5   2.1   1.4 43.7   5.02   4.40  183600.
 15   0     8.2     889.0                                             192032.
 15  40     7.8     884.0  14.3  4.9   2.3   1.5 42.7   4.56   4.40  216067.
 17  30     7.0     969.0                                             157624.
 19   0     6.4    1078.0  16.6  2.6   1.3   0.5 49.4   4.00   4.40  144504.
 20   0     5.9    1075.0                                             138600.
 22   0     4.9    1013.0  14.1  5.7   1.0   0.7 44.4   5.23   4.40  183000.
 22  30     4.8    1007.0                                              72134.
 25   0     3.9    1019.0                                             130353.
 25  45     3.6    1023.0  14.6  5.1   0.5   0.1 52.2   5.60   4.40  144380.
 27  30     3.1     980.0                                             103200.
 30   0     2.2     978.0  13.8  6.3   0.1   0.3 51.9   6.01   4.40  130353.
 32  30     1.5     950.0                                             131129.
 35   0     0.9     920.0  12.9  6.5   0.0   0.0 55.3   6.43   4.40  101129.
 37  30     0.2     851.0                                              86702.
--------------------------------------------------------------------------------
                           12.8  6.8   1.2        47.2  5.76   4.40
REMARKS                                                  ← 31% XS AIR

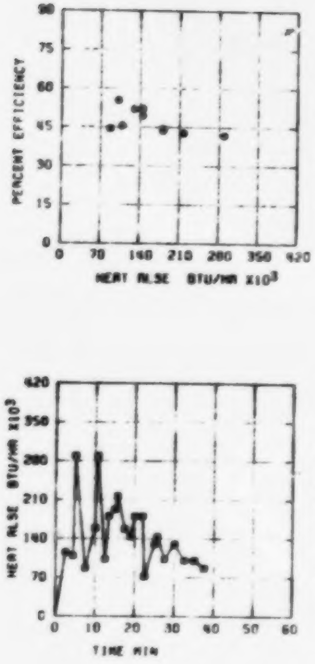
     AVERAGE HEAT RELEASED:   133886.1 BTU/HR           40% XS AIR

     AVERAGE HEAT OUTPUT  :    63691.2 BTU/HR

     AVERAGE EFFICIENCY   :      47.6 %
```

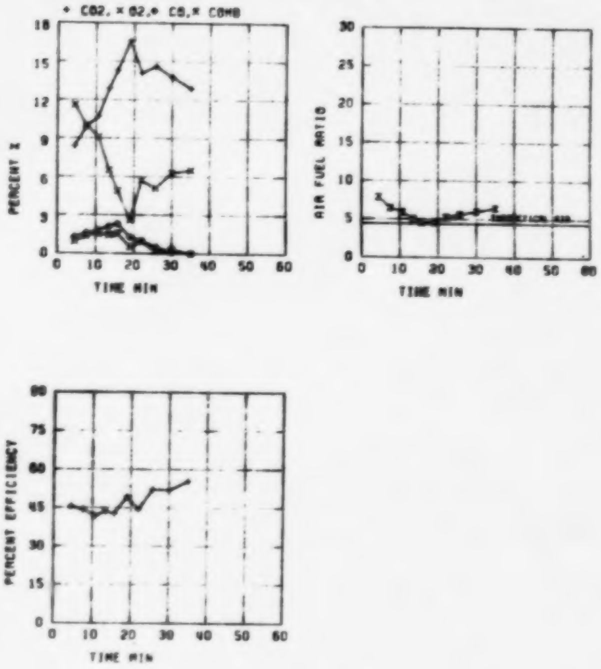
TEST NUMBER C-4

1-3/23/79



TEST NUMBER C-4

1-3/23/79



WOOD BURNING TEST RESULTS C-4

TEST NUMBER : 2-3/23/79

DATE OF TEST : MARCH 23, 1979

AMBIENT TEMPERATURE : 77 DEG F

DAMPER SETTING :
BOTH DAMPERS OPEN 1.5 TURNS

FUEL : WET PINE

MOISTURE CONTENT 30.0 % HHV= -6020.0

TIME		LBS WOOD	FLUE GAS TEMP (F)	%CO2	%O2	%CO	%COM	%EFF	A/F RATIO	THEO AIR	HEAT RLSD BTU/HR
0	0	24.5	356.0								0.
2	30	23.5	508.0								144480.
3	45	23.1	.485.0	10.2	8.8	0.8	0.0	64.5	7.48	4.40	115556.
5	0	22.3	477.0								231162.
7	30	21.4	467.0								130019.
9	0	20.8	458.0	7.2	13.6	0.2	0.9	47.9	10.13	4.40	144504.
10	0	20.4	442.0								144445.
12	30	19.6	464.0								115591.
15	0	18.5	469.0								158942.
15	55	18.3	505.0	9.6	10.5	1.6	1.7	42.0	6.37	4.40	123810.
17	30	17.5	588.0								150771.
20	0	16.3	580.0								173369.
20	53	15.8	601.0	10.9	8.7	0.7	0.0	61.5	7.30	4.40	204435.
22	30	15.0	641.0								173749.
25	0	13.9	683.0								173309.
26	55	13.3	699.0	13.0	6.2	2.9	3.4	54.0	3.98	4.40	94226.
27	30	12.5	696.0								495390.
30	0	11.3	697.0								173369.
31	0	10.7	711.0	9.2	10.2	1.6	0.3	40.2	7.04	4.40	216007.
32	30	10.1	719.0								144304.
35	0	9.0	722.0								158942.
36	30	8.3	724.0	14.3	5.0	1.7	0.9	52.1	4.93	4.40	163390.
37	50	7.9	727.0								144445.
40	0	6.9	759.0								144480.
42	30	6.1	820.0								130033.
43	0	5.8	824.0	14.6	5.5	0.8	1.3	43.0	4.98	4.40	144445.
45	0	5.4	837.0								72222.
47	30	4.7	798.0								101129.
50	0	4.2	791.0								72240.
52	30	3.7	803.0								72240.
55	0	3.1	766.0	12.8	7.2	0.2	0.1	59.1	6.53	4.40	57813.
57	30	2.4	729.0								72240.
60	0	2.5	652.0								43351.
62	30	2.2	574.0								43316.
65	0	2.0	524.0								28924.
67	30	1.8	490.0								28809.
70	0	1.6	481.0								26389.
72	30	1.5	447.0								14402.
75	0	1.3	420.0	5.4	14.7	0.5	0.0	57.4	14.28	4.40	28889.

C-4

REMARKS

AVERAGE HEAT RELEASED: 111730.8 BTU/HR

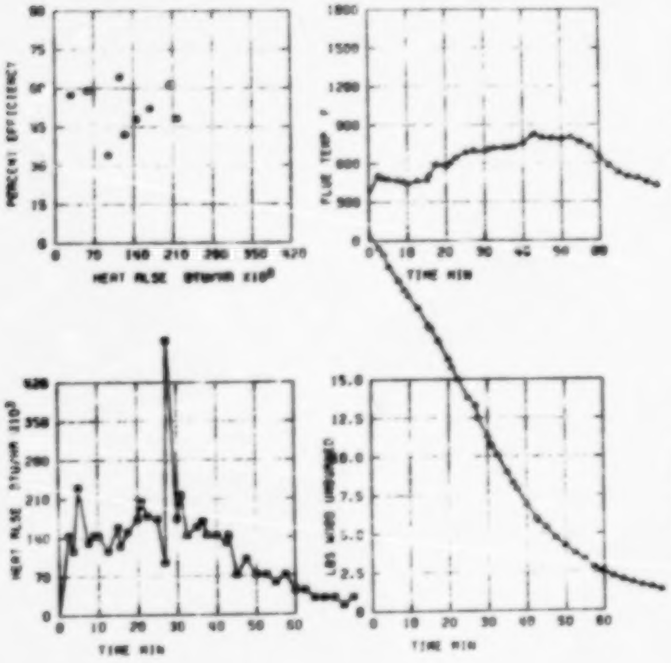
AVERAGE HEAT OUTPUT : 56662.9 BTU/HR

AVERAGE EFFICIENCY : 50.7 %

TEST CONDUCTED BY MIKE & BURT

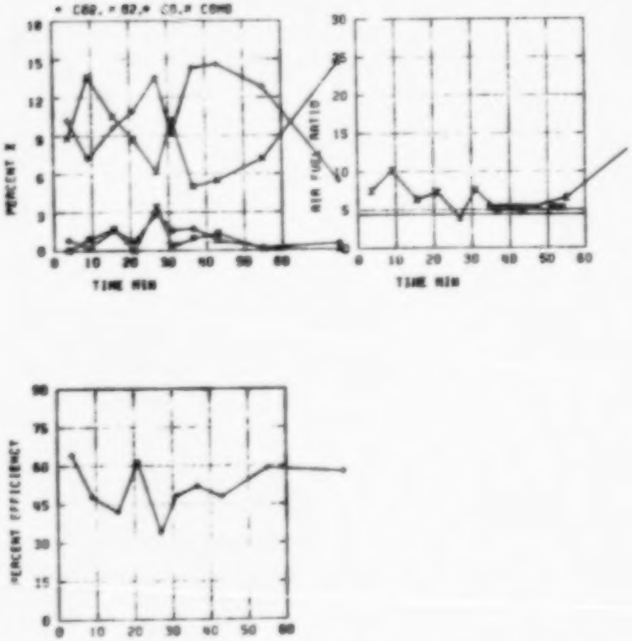
TEST NUMBER C-4

2-3/23/79



TEST NUMBER C-4

2-3/23/79



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                 WOOD BURNING TEST RESULTS   C-4
                                             NOx 2a,2b,2c
TEST NUMBER     :  1-3/26/79                 OHSM #835

DATE OF TEST    :  MARCH 26, 1979

AMBIENT TEMPERATURE :      69  DEG F

DAMPER SETTING :
                        BOTH DAMPERS OPEN TWO TURNS

FUEL  :  WET PINE

MOISTURE CONTENT  30.0 %            HHV=    -6020.0


  TIME   LBS WOOD FLUE GAS %CO2   %O2   %CO  %CH4  %EFF   A/F    THEO  HEAT RLSE
                  TEMP (F)                                 RATIO   AIR    BTU/HR

  0   0   24.2     482.0                                                      0.
  2  30   23.8     437.0                                                  57778.
  5   0   23.1     380.0   3.6  17.2   0.7   1.0  25.2  15.59   4.40     101164.
  7  30   22.5     360.0                                                  86667.
 10   0   22.1     475.0                                                  57813.
 12  30   21.3     504.0                                                 115556.
 14  15   20.6     502.0   7.7  12.7   1.2   1.5  38.2   7.94   4.40     144520.
 15   0   20.3     497.0                                                 144360.
 17  30   19.4     486.0                                                 133333.
 20   0   18.4     498.0                                                 144480.
 20  45   18.1     499.0   8.9  11.1   2.1   2.1  30.1   6.23   4.40     144504.
 22  30   17.4     503.0                                                 144470.
 25   0   16.4     484.0                                                 144480.
 27  30   15.6     489.0                                                 115591.
 30   0   14.8     474.0                                                 115556.
 32  30   14.1     499.0                                                 101164.
 34  30   13.3     468.0   6.9  13.0   1.9   1.3  37.1   8.15   4.40     144445.
 35   0   13.1     465.0                                                 144621.
 37  30   12.5     518.0                                                  86667.
 40   0   11.9     595.0                                                  86702.
 42  30   11.3     660.0                                                  86667.
 44   0   10.9     714.0   9.1  10.4   1.8   0.7  42.6   7.21   4.40      90355.
 45   0   10.3     661.0                                                 216667.
 47  30    9.9     779.0                                                  57813.
 50   0    9.0     676.0                                                 130018.
 52  30    8.9     791.0                                                 144432.
 54   0    8.5     830.0  10.6   9.9   0.8   1.6  30.6   6.39   4.40      90296.
 55   0    8.0     804.0                                                 180000.
 57  30    7.2     780.0                                                 115591.
 60   0    6.7     767.0                                                  72240.
 62  30    6.0     761.0  12.3  10.2   0.4   5.2  19.6   4.31   4.40     101129.
 65   0    5.5     725.0                                                  72240.
 67  30    5.0     706.0                                                  72240.
                                C-4
 70   0    4.8     725.0                                                  28894.
 72  30    4.0     709.0                                                 115591.
 75   0    3.7     704.0   9.2  13.3   0.5   4.9  10.8   5.50   4.40      43351.
 77  30    3.2     677.0                                                  72240.
 80   0    2.9     664.0                                                  43351.
 82  30    2.4     643.0                                                  72240.
 85   0    1.9     634.0                                                  72240.
 87  30    1.6     574.0                                                  43351.
 90   0    1.3     557.0   6.8  13.4   0.7   0.3  48.9  10.84   4.40      43316.

REMARKS

     AVERAGE HEAT RELEASED:    91904.9 BTU/HR

     AVERAGE HEAT OUTPUT  :    30019.9 BTU/HR

     AVERAGE EFFICIENCY   :       32.7 %

                    TEST CONDUCTED BY:BURT, MIKE, & GLENN
```
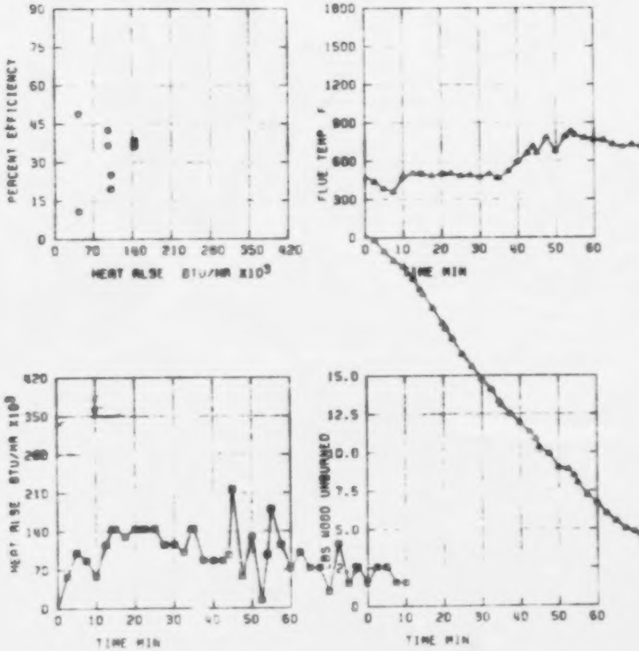
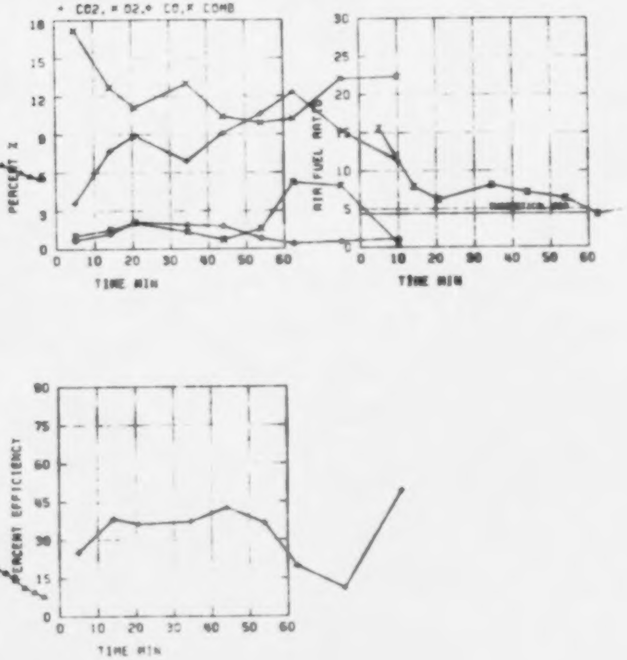

TEST NUMBER C-4
1-3/26/79



TEST NUMBER C-4
1-3/26/79



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                     WOOD BURNING TEST RESULTS  C-4
                                                BIRDSALL
TEST NUMBER    :  1-3/27/79                     ALDERFOE

DATE OF TEST   :  MARCH 27, 1979   10:10 → 11:20

AMBIENT TEMPERATURE :      70  DEG F

DAMPER SETTING :
                        BOTH DAMPERS OPEN 2 1/2 TURNS

FUEL  :  WET PINE

MOISTURE CONTENT  30.0 %           HHV=    8620.0


  TIME  LBS WOOD FLUE GAS %CO2  %O2  %CO %COM %EFF  A/F   THEO HEAT RLSE
                 TEMP (F)                           RATIO  AIR   BTU/HR

   0  0    23.3    434.0                                                0.
   2 30    19.7    460.0                                            86732.
   5  0    19.1    461.0   6.8 13.5  0.8  0.8 45.2  9.93  4.40     86067.
   7 30    18.4    524.0                                           101129.
  10  0    17.6    515.0   7.2 12.0  0.9  0.0 55.5 10.15  4.40    115591.
  12 30    16.9    681.0                                           101129.
  15  0    15.9    731.0                                           144480.
  17  0    15.0    760.0  11.1  8.3  1.6  0.5 46.5  5.86  4.40    162306.
  17 30    14.8    765.0                                           144445.
  20  0    13.8    770.0                                           144480.
  21 30    13.1    822.0  13.9  4.9  2.2  0.5 50.7  5.06  4.40    168540.
  22 30    12.6    836.0                                           180000.
  25  0    11.5    858.0                                           158942.
  26  0    11.1    873.0  13.6  5.4  2.3  1.0 45.1  4.92  4.40    144445.
  27 30    10.4    903.0                                           163340.
  30  0     9.4    933.0  13.8  5.5  2.3  1.6 39.6  4.64  4.40    144480.
  32 30     8.3    980.0                                           153042.
  35  0     7.3    942.0  12.5  4.8  1.5  0.0 50.4  5.57  4.40    144480.
  37 30     6.4   1050.0                                           150615.
  40  0     5.6    968.0                                           115341.
  41 30     5.1    969.0  14.0  5.9  0.3  0.2 55.0  5.89  4.40    122430.
  42 30     4.8    954.0                                           108376.
  45  0     4.1    939.0                                           101129.
  47 30     3.5    918.0                                            86732.
  50  0     2.9    913.0  13.5  6.5  0.4  0.4 51.4  5.72  4.40     86067.
  52 30     2.4    766.0                                            72240.
  55  0     2.0    685.0                                            57813.
  57 30     1.7    653.0                                            43351.
  60  0     1.4    647.0                                            43316.
  62 30     1.1    617.0   8.0 11.5  1.3  0.0 52.7  9.02  4.40     43351.
  65  0     0.8    603.0                                            43351.

REMARKS                   C-4

     AVERAGE HEAT RELEASED:  108339.9 BTU/HR

     AVERAGE HEAT OUTPUT  :    53377.9 BTU/HR

     AVERAGE EFFICIENCY   :       49.0 %

                   CONDUCTED BY GLENN AND BURT
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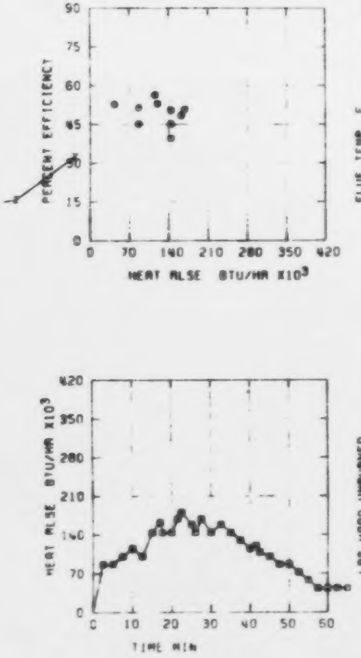
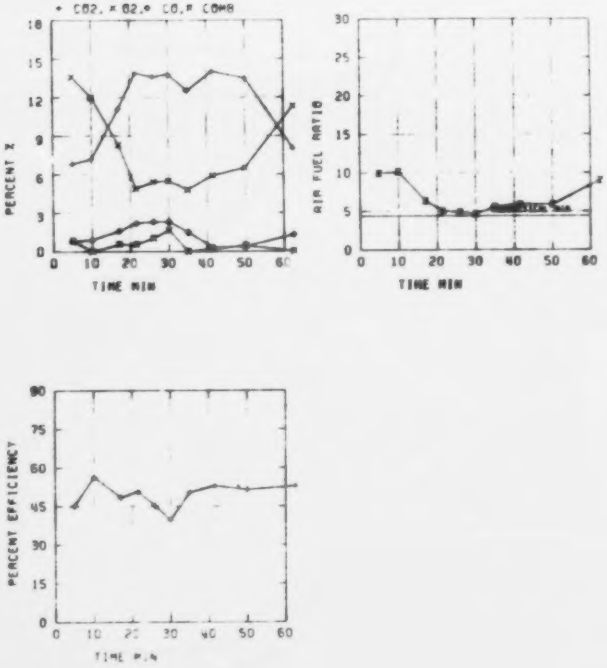
TEST NUMBER C-4

1-3/27/79



TEST NUMBER C-4

1-3/27/79



APPENDIX B

STATISTICAL ANALYSES FOR PARTICULATE, CONDENSABLE ORGANICS, NITROGEN OXIDES AND CARBON MONOXIDE EMISSIONS DATA

METHOD

The three controlled variable factors during this sampling program were 1) combustion equipment type, 2) wood type, and, in some instances, 3) sampling method. A statistical analysis was performed to determine if the type of wood burned and/or type of combustion equipment employed had a significant effect on pollution emission rates, expressed as grams of pollutant emitted per kilogram of wood burned.

The Analysis of Variance (ANOVA) technique was used to determine which factors in an experiment or test account for the greatest variation in a measured parameter. In this case the ANOVA technique was used to determine if the type of combustion equipment, the type of wood, or both, cause a significant change in pollution emission rates during controlled burning experiments. This technique determines which of these two factors is significant. However, if a large error term in the ANOVA matrix indicates that 1) a large systematic error is present, or 2) a factor not accounted for in the experiment (such as, for example, amount of oxygen available) is causing the significant change in the measured parameters.

The students' "t" test was employed to determine if the mean emission rates for the two sources could have come from the same population. For example: Given a mean emission rate for fireplaces ($\bar{X}_1$) and a mean emission rate for wood stoves ($\bar{X}_2$), does $\bar{X}_1 = \bar{X}_2$?

Assuming unequal population variances ($\sigma_1^2 \neq \sigma_2^2$), the t statistic is computed as follows:

$$t = \frac{|\bar{X}_1 - \bar{X}_2|}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

and

$$\nu = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 - 1}} \qquad \text{(B-1)}$$

where $\bar{X}_1, \bar{X}_2$ = the means of the emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, for stoves and fireplaces, respectively
s_1^2, s_2^2 = the associated variances
n_1, n_2 = the number of data points
ν = the number of degrees of freedom for t

Once the t statistic is obtained, it is compared with the standard tabulated statistical value for the same number of degrees of freedom. A "t" value greater than that given in the tables indicates a statistically significant difference in the means, i.e., the means are not from the same population. A "t" value less than or equal to the table value indicates that there is no statistical difference in the means.

The following discussions describe the statistical analysis for carbon monoxide (CO), nitrogen oxides (NO_x), condensable organics, and particulate emission rates. It was assumed that 1) combustion equipment, 2) type of wood, and 3) sampling method were the major contributors to variation in emission rate levels. Table B-1 shows the maximum number of levels for each factor used in the ANOVA matrix.

TABLE B-1. ANOVA MATRIX FACTOR LEVELS

Wood type	Combustion equipment	Sampling method
Seasoned oak	Fireplace	EPA Methods
Green oak	Baffled stove	SASS Train
Seasoned pine	Non-baffled stove	
Green pine		
No. of levels = 4	No. of levels = 3	No. of levels = 2

CARBON MONOXIDE (CO) ANALYSIS

The student's "t" test showed that there was no difference in the mean emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, for the baffled and non-baffled stoves. These data were combined and a (4 x 2) matrix of 4 wood types and 2 combustion types were run through ANOVA. Differences in sampling equipment were not included due to lack of data.

TABLE B-2. ANOVA MATRIX FOR CO EMISSIONS

Factor	DF	SS	MS	$F_{calc.}$	F_{table} (90%)	Variance, %
Wood type	3	8779	2926	1.23	9.28	21
Combustion equipment	1	25536	25536	3.54	10.13	62
Error	3	7127	2376	-	-	17
Total	7	41441	0	-	-	-

Although a large portion of the variance (62%) is due to the combustion equipment factor, this variation is not significant at the 90% level. This factor has only two levels (fireplace and stove), so its effect cannot be adequately measured. Furthermore, this experiment was not replicated; therefore, random and systematic error is confounded. In order to determine if, indeed, these factors are significant, more data are needed. Otherwise, another factor as yet unaccounted for may have had more significance than those chosen.

NITROGEN OXIDES (NO_x) ANALYSIS

An analysis of variance (ANOVA) was also performed to determine whether the type of wood burned and/or the type of combustion equipment had a significant effect on the NO_x emissions. The resulting ANOVA matrix is shown in Table B-3.

TABLE B-3. ANOVA MATRIX FOR NO_x EMISSIONS

Factor	DF	SS	MS	$F_{calc.}$	R_{table} (90%)	Variance, %
Wood type	3	0.876	0.292	0.0046	2.20	1.9
Combustion equipment	2	23.6	11.8	1.24	2.42	50
Interaction	6	1.39	0.231	-	-	3
Replicates	5	1.70	0.340	-	-	3.6
Error	55	19.0	0.345	-	-	40
Total	71	47.0	-			

A large portion of the variance (50%) in this experiment was caused by the type of combustion equipment. However, the error term is also large (40%); therefore, the F value is low (1.24). It can not be concluded that the combustion equipment type causes a statistically significant effect at the 90% confidence level because the error term obscures this effect. The large error term indicates that an "unknown" factor was not accounted for in the experiment or that the systematic error was very large.

To determine if the mean NO_x emission rates, expressed as grams of pollutant emitted per kilogram of wood burned, differed significantly among the three combustion equipment types, a student "t" test for equality of means was performed. This test indicates that the two means are from different populations, i.e., it can be concluded that the NO_x emissions from the fireplaces were higher than the emissions from the stoves. For this test, the data from the two stove types were combined and treated as one factor since there was no statistical difference between them.

PARTICULATE EMISSIONS ANALYSIS

The combustion equipment - sampling method interaction caused the most variation but neither of these factors caused a statistically significant variation. Without replication of sampling runs, the error term is confounded (see Table B-4).

TABLE B-4. ANOVA MATRIX FOR PARTICULATE EMISSIONS

Factor	DF	SS	MS	$F_{calc.}$	F_{table}	Variance, %
Combustion equipment	3	10.598	3.533	1.3	4.76	19
Sampling method	1	4.717	4.717	0.58	5.99	9
Wood type	2	5.46	2.73	0.67	5.14	10
Interaction	3	15.03	5.01	1.85	4.76	27
Error	6	8.137	1.356	-	-	15
Total	23	55.24	-	-	-	-

CONDENSABLE ORGANIC EMISSION ANALYSIS

An anlysis of variance indicates that the type of wood burned causes a significant variation in the condensable organic emission rates, expressed as grams of pollutant emitted per kilogram of wood burned. The type of equipment employed is not significant (see Table B-5).

TABLE B-5. ANOVA MATRIX FOR CONDENSABLE ORGANIC EMISSIONS

Factor	DF	SS	MS	$F_{calc.}$	$F_{table\ (95\%)}$	Variance, %
Wood	3	68.74	22.91	6.76	4.76	86
Combustion equipment	2	1.096	0.5481	0.11	5.14	1.4
Error	6	10.17	1.695	-	-	13
Total	11	80.011	-	-	-	-

APPENDIX C

POM AUDIT SAMPLE RESULTS

This Appendix provides the results of an audit sample containing POM's submitted to MRC by Research Triangle Institute, Inc. at the request of the EPA Process Measurements Branch and Special Studies group. Although the intention of this audit was to verify results of a recently completed study on residential coal-fluid systems, it was also viewed as having utility in the quality assurance area of this program on wood-fired combustion.

The audit sample containing a prepared mixture of POM's was coded and submitted for GC/MS analysis along with the POM train and SASS train samples in this study. A summary of the audit sample results appears below in Table C-1.

TABLE C-1. SUMMARY OF POM AUDIT SAMPLE ANALYSIS

RTI mixture	MRC identification	RTI Gravimetric mixture	RTI analysis	MRC GC/MS analysis
1,2-Benzanthracene, MW 228	Benzanthracene/chrysene, MW 228	205	171	
Chrysene, MW 228		159		
Triphenylene, MW 228		103	194	467[a]
7,12 DMBA, MW 256	7,12 DMBA (or isomers), MW 256	90	80	121
Benz(a)pyrene, MW 252	Benz(a or e) pyrene/perylene, MW 252	49	41	61
--	Napthobenzothiophene, MW 234	b	b	12

[a] Isomers not resolved by MRC GC/MS system.

[b] Possible contaminant, not added to RTI mixture.

Background information and details of the analysis are provided in the following texts taken from RTI and MRC reports and correspondence.

GC/MS ANALYSIS FOR POM'S IN RTI PAH-1

Two vials were submitted for quantitative/qualitative GC/MS analysis of POM content (given in terms of micrograms per milliliter). The two vials were the same, both designated as RTI PAH-I, so only one analysis was made. The solvent was determined to be benzene. The analysis was performed on the HP5983-A GC/MS system under the following GC conditions:

1/4" x 6" (0.006 m x 0.15 m) glass column packed with 3% Dexsil 400 on Chromasorb W-MP
160°C - 2 min/8°C per min/300°C - 15 min
Helium Flow: 30 mL/min

Initial runs were made to identify POM species present. Four peaks were observed: Major peak - molecular ion 228 at ∿11.5 min, 2nd largest peak - molecular ion 256 at ∿14.5 min, 3rd largest peak - molecular ion 252 at ∿15.6 min, and the 4th weak peak - molecular ion 234 at ∿11.2 min. Because of the wide range in concentration levels, a special standard mix was prepared to approximate the concentrations of the sample. The identification of the POM's based on spectra and retention time are as follow:

(1) Mol. Wt. 234 → Napthobenzothiophene
(2) Mol. Wt. 228 → Benz(a)anthracene or chrysene (or other 4-fused ring isomers
(3) Mol. Wt. 256 → C_2-alkyl-benzanthracene/-benzphenanthrene/-chrysene, e.g., 7,12-dimethyl benz(a)anthracene
(4) Mol. Wt. 252 → Benz(a or e)pyrene/perylene (retention time too late for benzofluoranthenes)

Standards used for quantitation were napthobenzothiophene (1,2-benzodiphenylene sulfide), benz(a)anthracene, 7,12-dimethly-benz(a)anthracene, and benz(a)pyrene. Calculations and quantitation are shown below.

Calculations: Standard Response → Peak Area ÷ Concentration $\left(\mu g/mL = \frac{Area}{\mu g/mL}\right)$

Sample Concentration → Peak Area ÷ Standard Response $\frac{Area}{\mu g/mL}$ = µg/mL

2 standard runs made and averaged; 2 sample runs made and averaged.

Napthobenzothiophene

Standard Response:	9793 ÷ 55 µg/mL → 178 µg/mL	171 per µg/mL
	8967 ÷ 55 µg/mL → 163 µg/mL	
Sample Concentration:	1878 ÷ 171 µg/mL → 11 µg/mL	12 µg/mL
	2171 ÷ 171 µg/mL → 13 µg/mL	

Benz(a)anthracene/chrysene (or isomer)

Standard Response:	75567 ÷ 365 µg/mL → 207/µg/mL 70071 ÷ 365 µg/mL → 192 µg/mL	200 µg/mL
Sample Concentration:	88134 ÷ 200/µg/mL → 441 µg/mL 98718 ÷ 200/µg/mL → 494 µg/mL	467 µg/mL

C_2-alkylbenzanthracenes (e.g., 7,12-Dimethylbenz(a)anthracene)

Standard Response:	4778 ÷ 75 µg/mL → 64/µg/L 3980 ÷ 75 µg/mL → 53/µg/L	59 µg/mL
Sample Concentration:	6029 ÷ 59 µg/mL → 102 µg/L 8203 ÷ 59 µg/mL → 139 µg/L	121 µg/mL

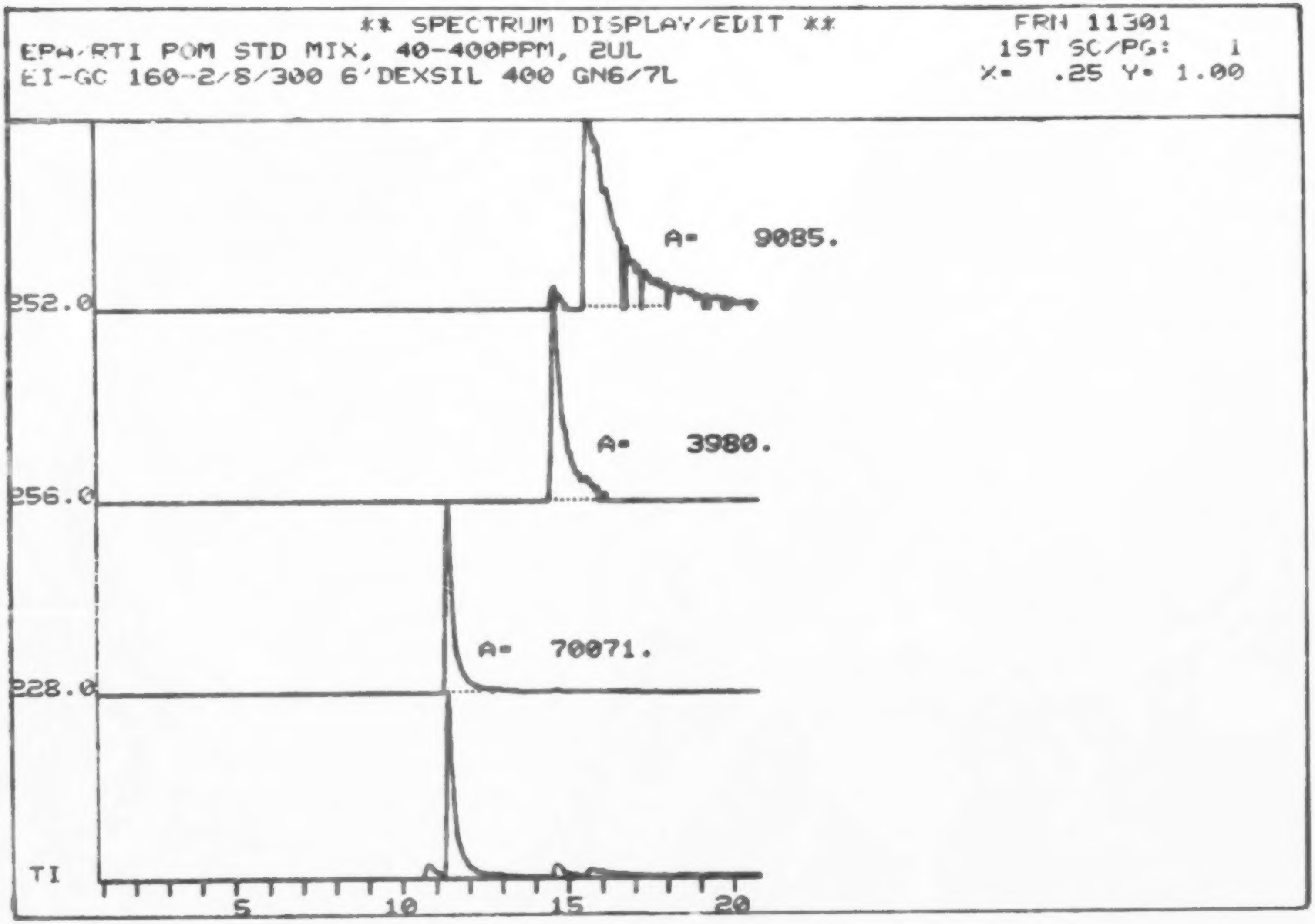
Benz(a or e)pyrene/Perylene

Standard Response:	10573 ÷ 60 µg/mL → 176/µg/mL 9085 ÷ 60 µg/mL → 151/µg/mL	164 µg/mL
Sample Concentration:	9717 ÷ 164/µg/mL → 59 µg/mL 10229 ÷ 164/µg/mL → 62 µg/mL	61 µg/mL

Results Summary:

Napthobenzothiophene	→ 12 µg/mL
Benz(a)anthracene/chrysene (or isomer)	→ 467 µg/mL
C_2-alkylbenzanthracene (or isomer)	→ 121 µg/mL
Benz(a or e)pyrene/perylene	→ 61 µg/mL

Attached are the chromatograms/ion traces (234 ion trace not shown) for both sample runs as well as the mass spectra of the compounds and the area tables. The same is attached for one of the standard runs. Some "splitting" occurred for mass above 250 AMU but it is felt that since there should be an equal chance of occurrence for both sample and standard mix, the average of two runs for each should produce acceptable results.



```
** SPECTRUM DISPLAY/EDIT **                    FRN 11301
EPA/RTI POM STD MIX, 40-400PPM, 2UL            1ST SC/PG:    1
EI-GC 160-2/8/300 6'DEXSIL 400 GN6/7L         X=   .25 Y= 1.00
```

Area Table for both standard runs

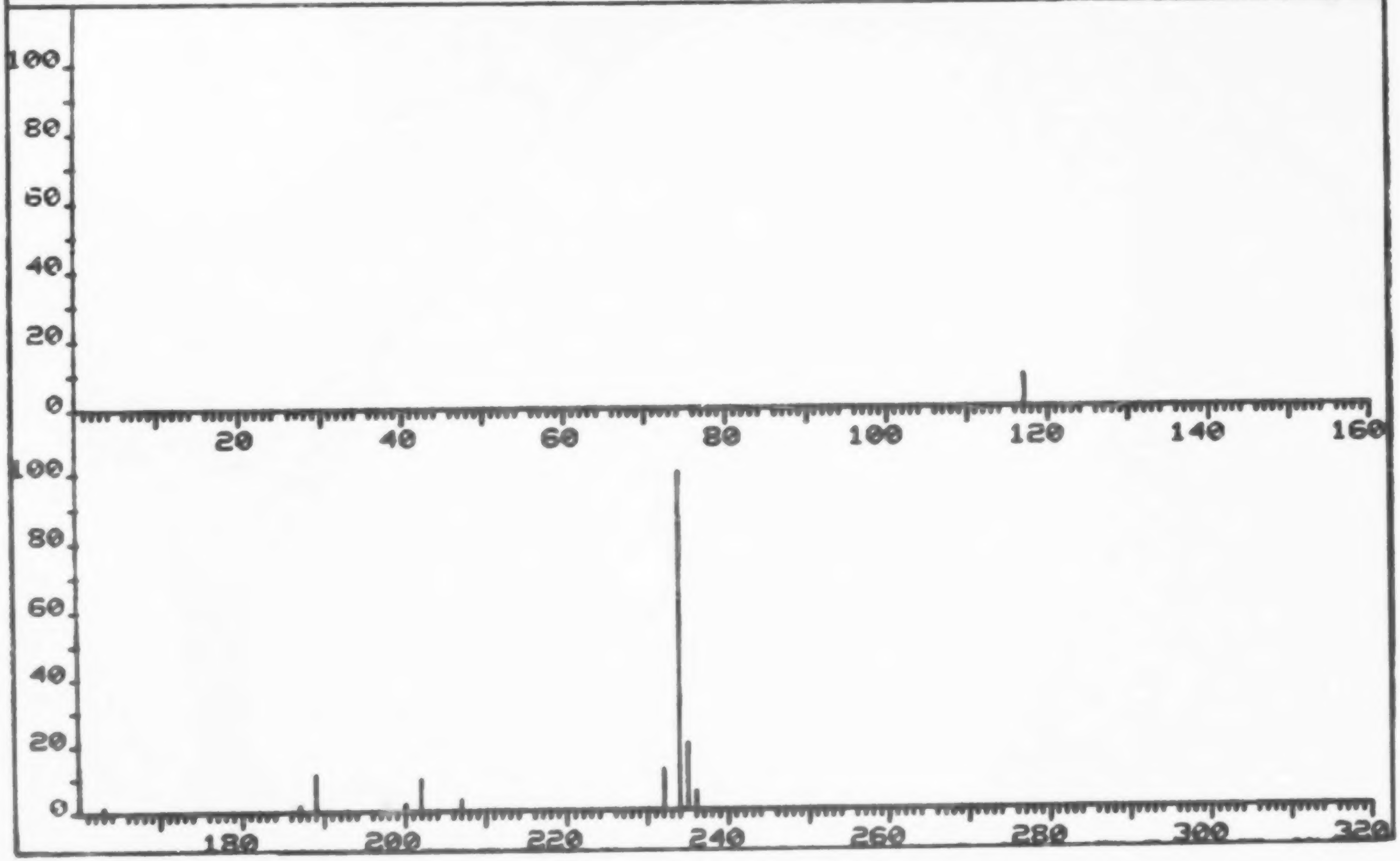
```
FILE NUMBER 11301

ENTRY  TIME    MASS     AREA      %

  1    10.7   228.0    75567.   38.75
  2    13.9   256.0     4778.    2.45
  3    15.0   252.0    10573.    5.42
  4    10.0   234.0    10307.    5.29
  5    10.6   234.0      514.     .26
  6    11.4   228.0    70071.   35.93
  7    14.6   256.0     3980.    2.04
  8    15.8   252.0     9085.    4.66
  9    10.7   234.0     9543.    4.89
 10    11.3   234.0      576.     .30

CAL % ON ENTRY?
```

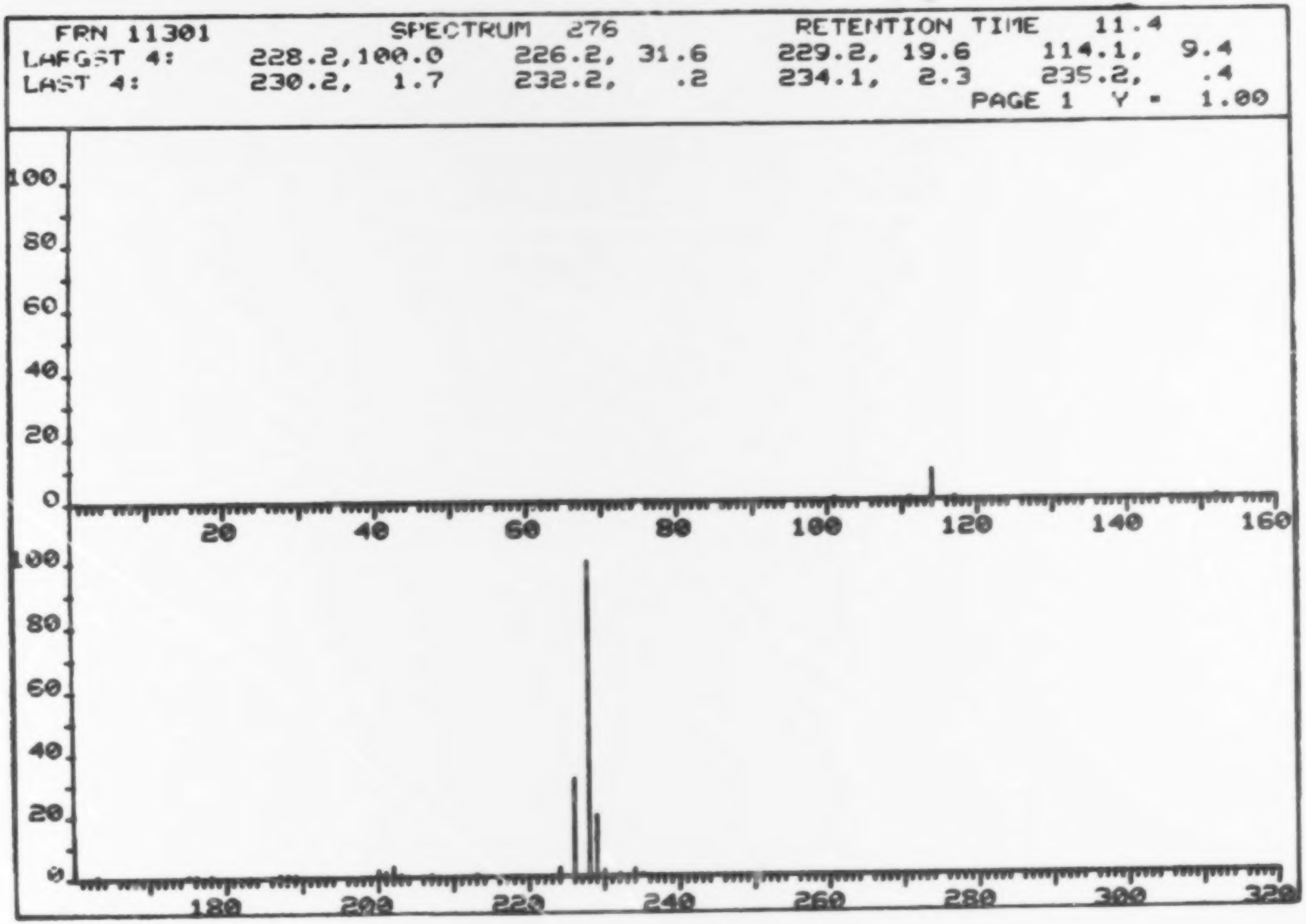
} 9793 ← (corrected for ion trace contribut; from 228 peak)

} 8967

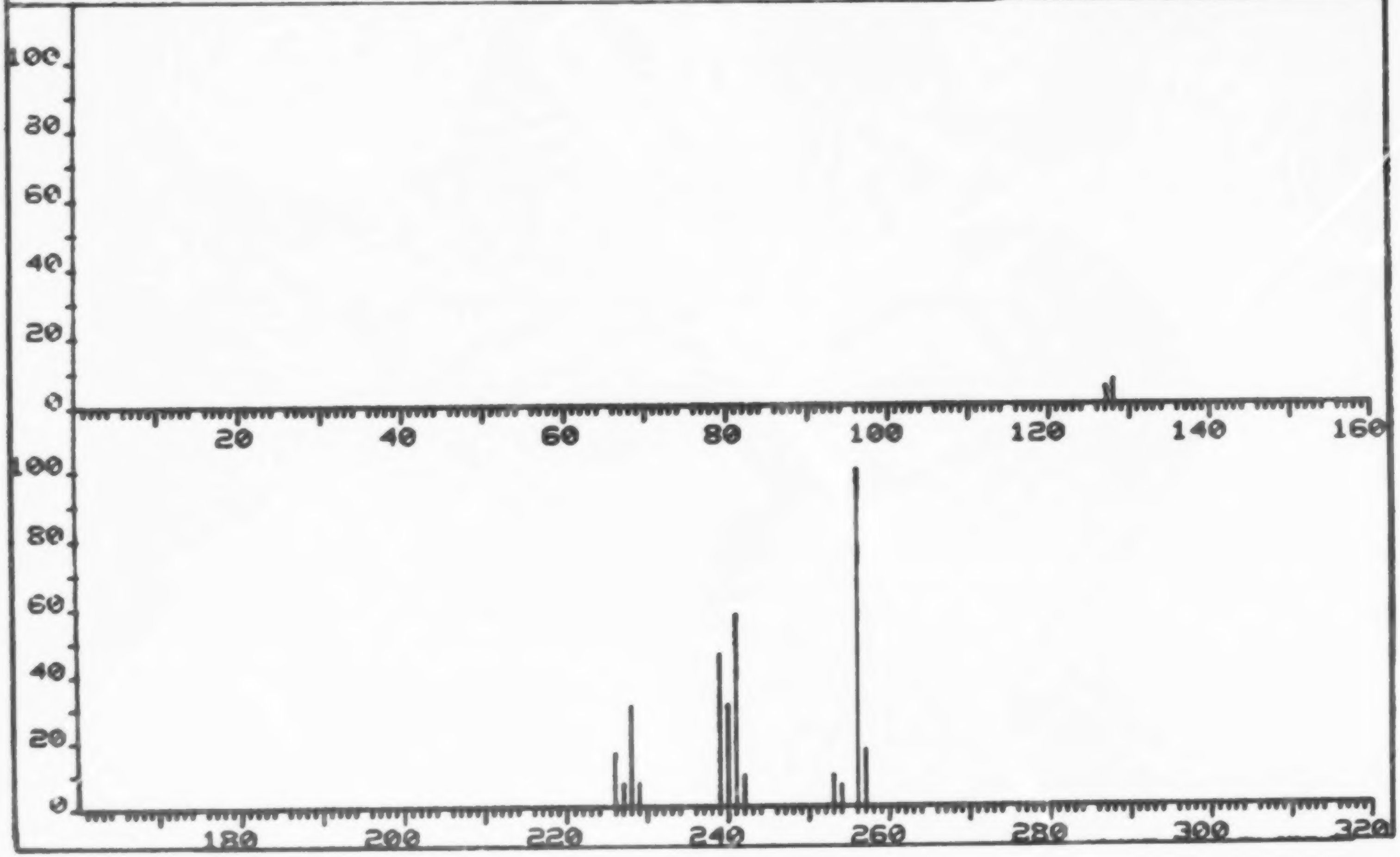
Time started late; add 0.7 min. to retention time

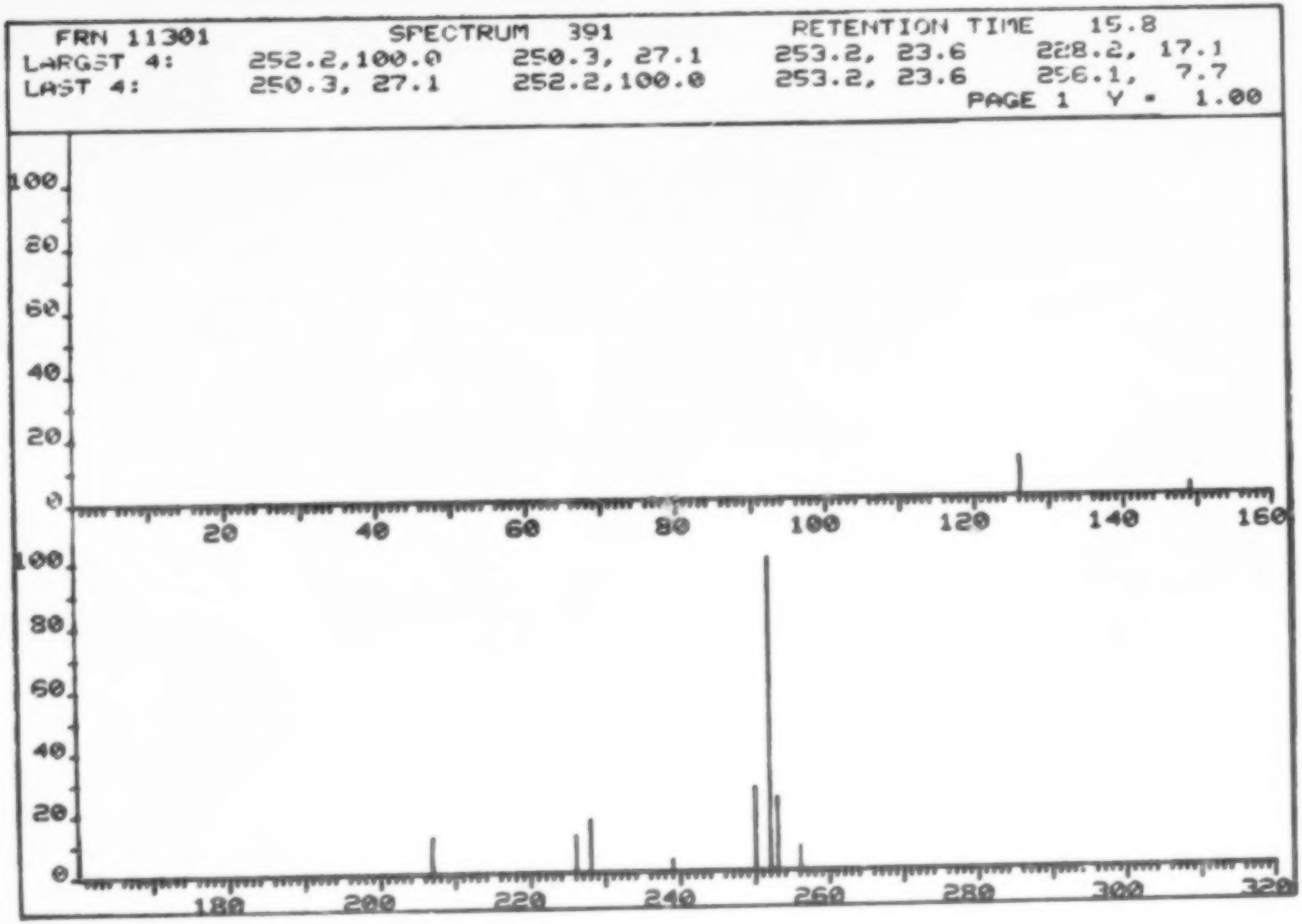
```
  FRN 11301              SPECTRUM  253              RETENTION TIME    10.7
LARGST 4:       234.1,100.0     235.1, 19.9     232.1, 12.1     189.1, 11.3
LAST 4:         232.1, 12.1     234.1,100.0     235.1, 19.9     236.2,  5.6
                                                               PAGE 1  Y =  1.00
```



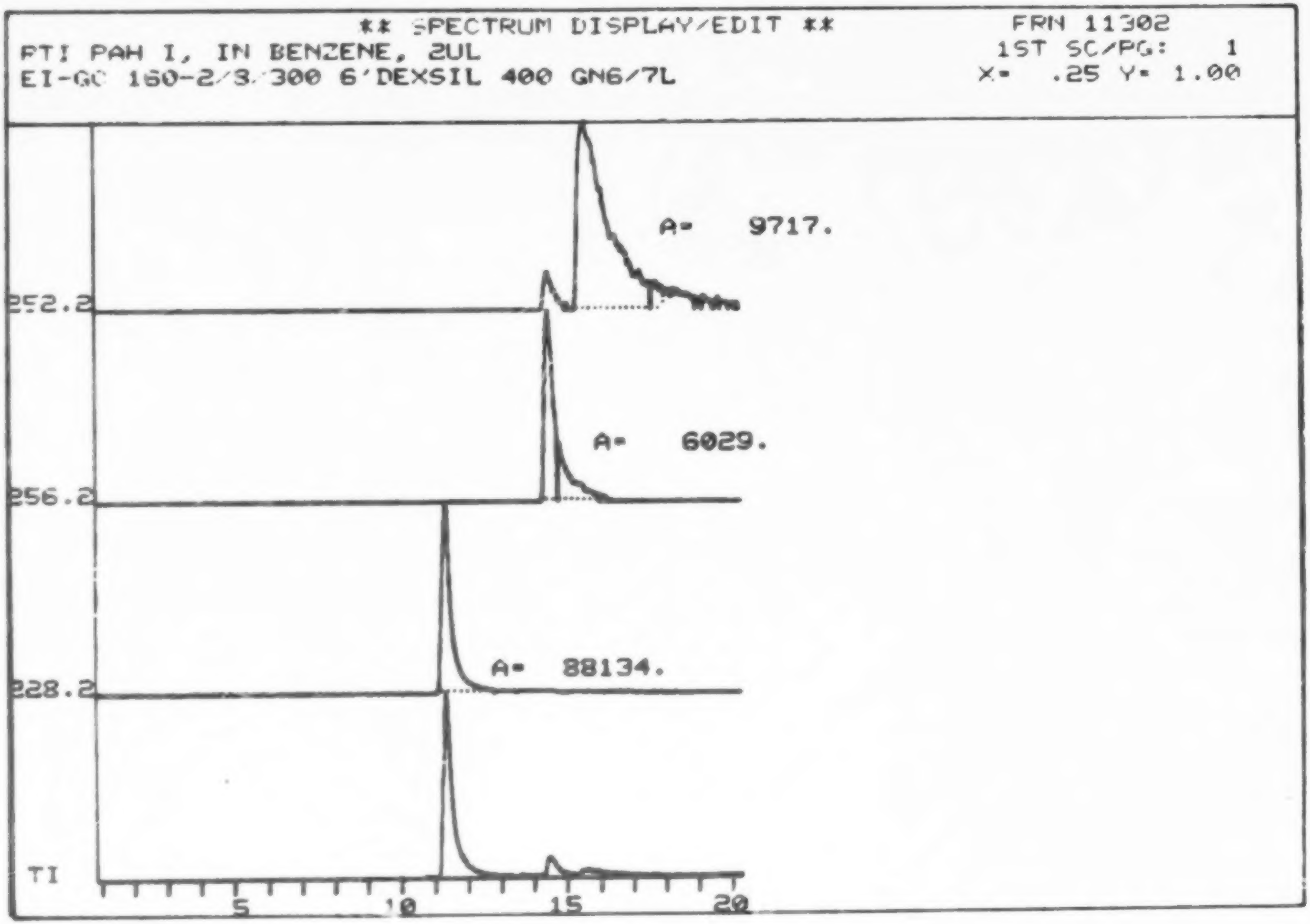


```
 FRN 11301              SPECTRUM  276             RETENTION TIME    11.4
LARGST 4:     228.2,100.0      226.2, 31.6     229.2, 19.6      114.1,   9.4
LAST 4:       230.2,   1.7     232.2,    .2    234.1,  2.3      235.2,    .4
                                                           PAGE 1  Y =  1.00
 FRN 11301            SPECTRUM  362              RETENTION TIME   14.7
LARGST 4:      256.2,100.0     241.2, 57.8    239.2, 46.0     240.2, 30.7
LAST 4:        253.3,  9.3     254.3,  6.2    256.2,100.0     257.2, 17.1
                                                          PAGE 1  Y =  1.00
```





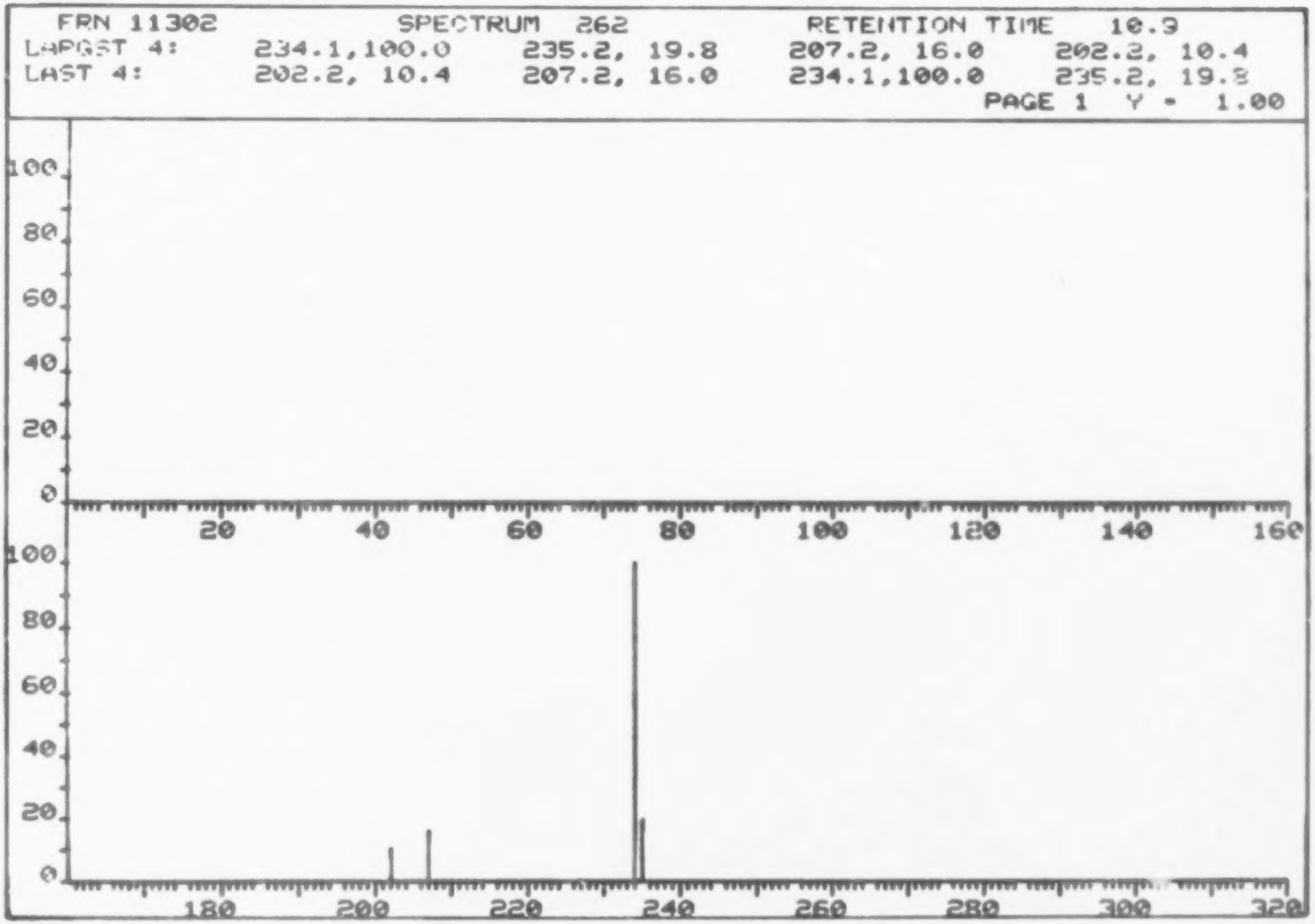
```
  FRN 11301            SPECTRUM   391            RETENTION TIME    15.8
LARGST 4:      252.2,100.0      250.3, 27.1      253.2, 23.6      228.2, 17.1
LAST 4:        250.3, 27.1      252.2,100.0      253.2, 23.6      256.1,  7.7
                                                              PAGE 1  Y =  1.00
```



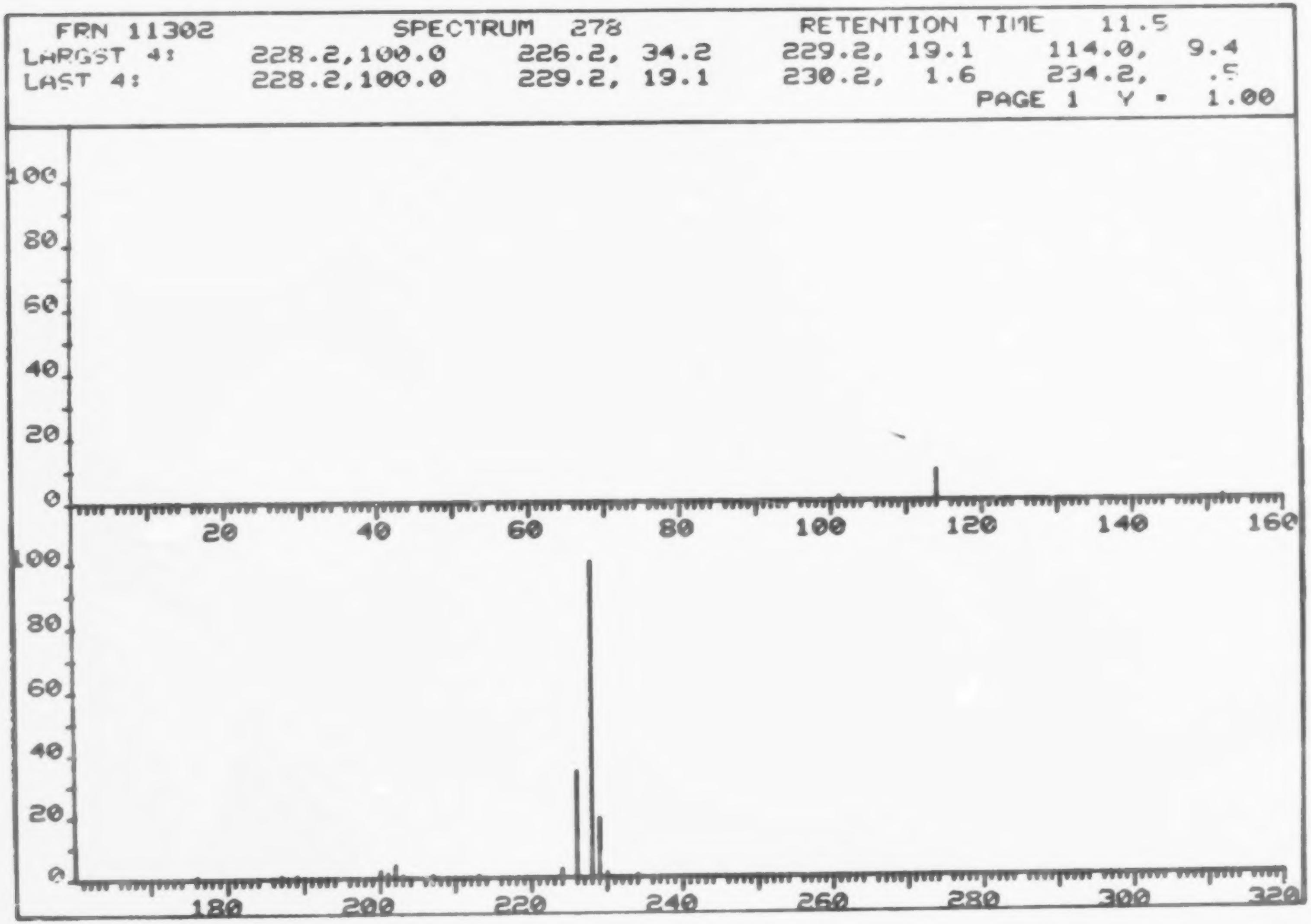
```
                    ** SPECTRUM DISPLAY/EDIT **              FRN 11302
RTI PAH I, IN BENZENE, 2UL                                  1ST SC/PG:    1
EI-GC 160-2/8/300 6'DEXSIL 400 GN6/7L                     X=  .25 Y= 1.00
```

```
FILE NUMBER 11302

ENTRY  TIME    MASS     AREA      %

   1   11.4   228.2    88134.   82.70
   2   14.5   256.2     6029.    5.66
   3   15.6   252.2     9717.    9.12
   4   11.2   234.0     2296.    2.15
   5   11.2   234.0      398.     .37

CAL % ON ENTRY?
```

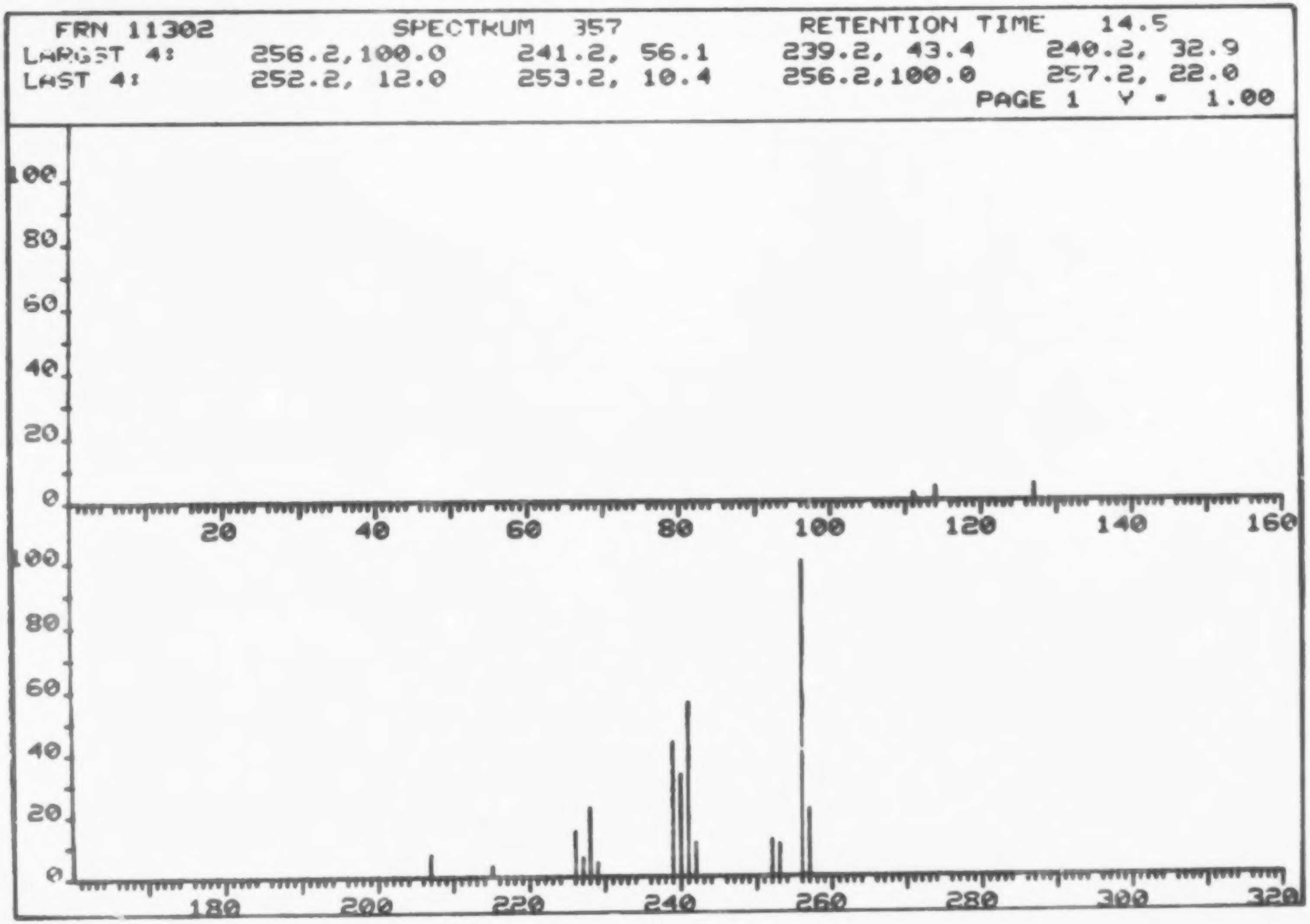
128



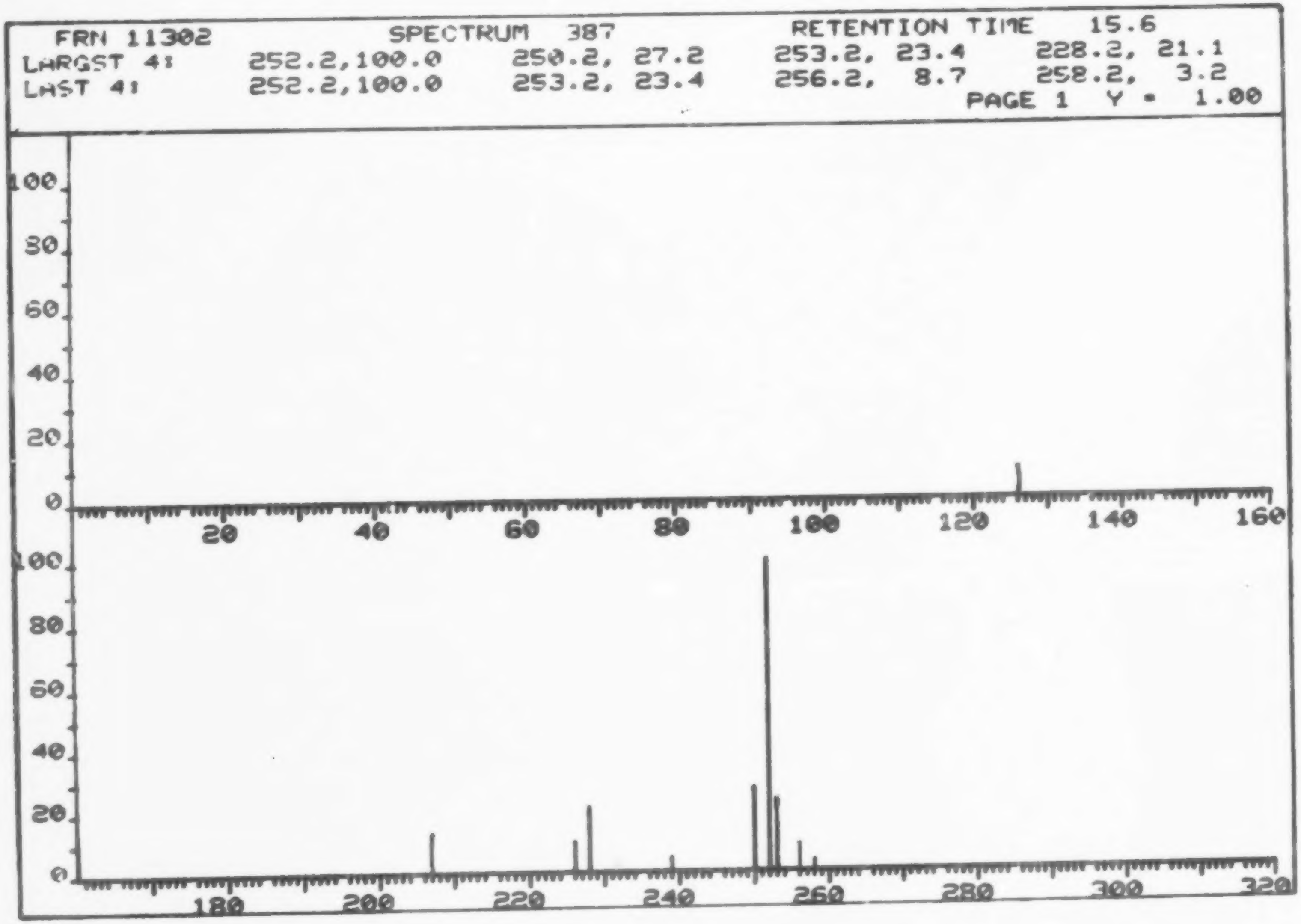
```
  FRN 11302             SPECTRUM  262              RETENTION TIME    10.9
LARGST 4:     234.1,100.0     235.2, 19.8     207.2, 16.0     202.2, 10.4
LAST 4:       202.2, 10.4     207.2, 16.0     234.1,100.0     235.2, 19.8
                                                          PAGE 1  Y -  1.00
```



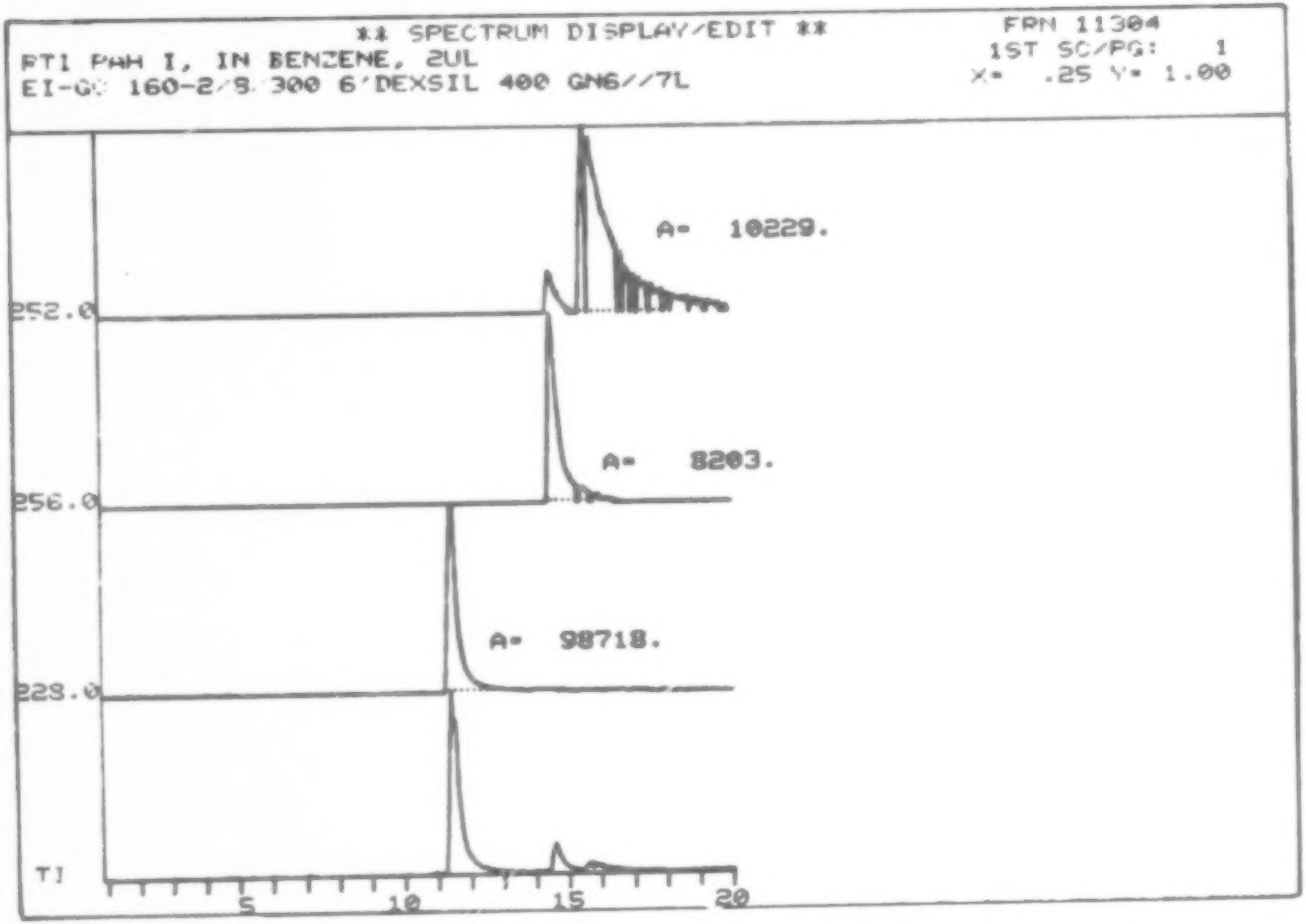
```
  FRN 11302            SPECTRUM  278            RETENTION TIME   11.5
LARGST 4:     228.2,100.0     226.2, 34.2     229.2, 19.1     114.0,   9.4
LAST 4:       228.2,100.0     229.2, 19.1     230.2,  1.6     234.2,    .5
                                                         PAGE 1  Y =  1.00
```



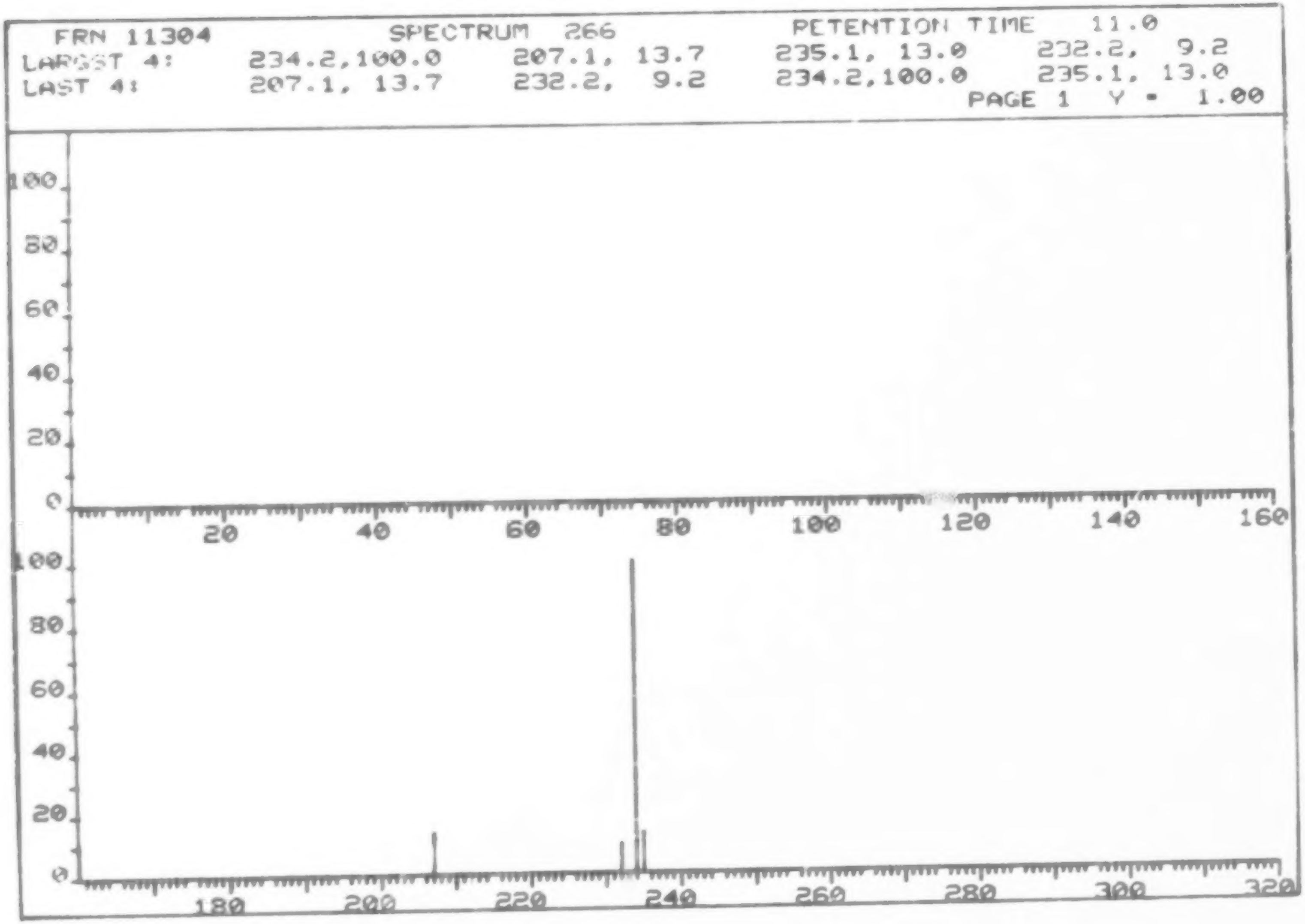
```
  FRN 11302            SPECTRUM  357            RETENTION TIME    14.5
LARGST 4:      256.2,100.0      241.2, 56.1      239.2, 43.4      240.2, 32.9
LAST 4:        252.2, 12.0      253.2, 10.4      256.2,100.0      257.2, 22.0
                                                             PAGE 1  Y =  1.00
```



```
FILE NUMBER 11304

ENTPY   TIME     MASS     AREA      %

   1    11.5    228.0    98718.   82.18
   2    14.5    256.0     8203.    6.83
   3    15.6    252.0    10229.    8.52
   4    11.3    234.0     2569.    2.14
   5    11.3    234.0      398.     .33

CAL % ON ENTRY?
```



```
                ** SPECTRUM DISPLAY/EDIT **              FRN 11304
RTI PAH I, IN BENZENE, 2UL                            1ST SC/PG:    1
EI-GC 160-2/8 300 6'DEXSIL 400 GN6//7L               X=   .25 Y= 1.00
```



```
FRN 11304              SPECTRUM  266              PETENTION TIME    11.0
LARGST 4:      234.2,100.0     207.1, 13.7     235.1, 13.0     232.2,   9.2
LAST 4:        207.1, 13.7     232.2,   9.2    234.2,100.0     235.1, 13.0
                                                          PAGE 1   Y =   1.00
```

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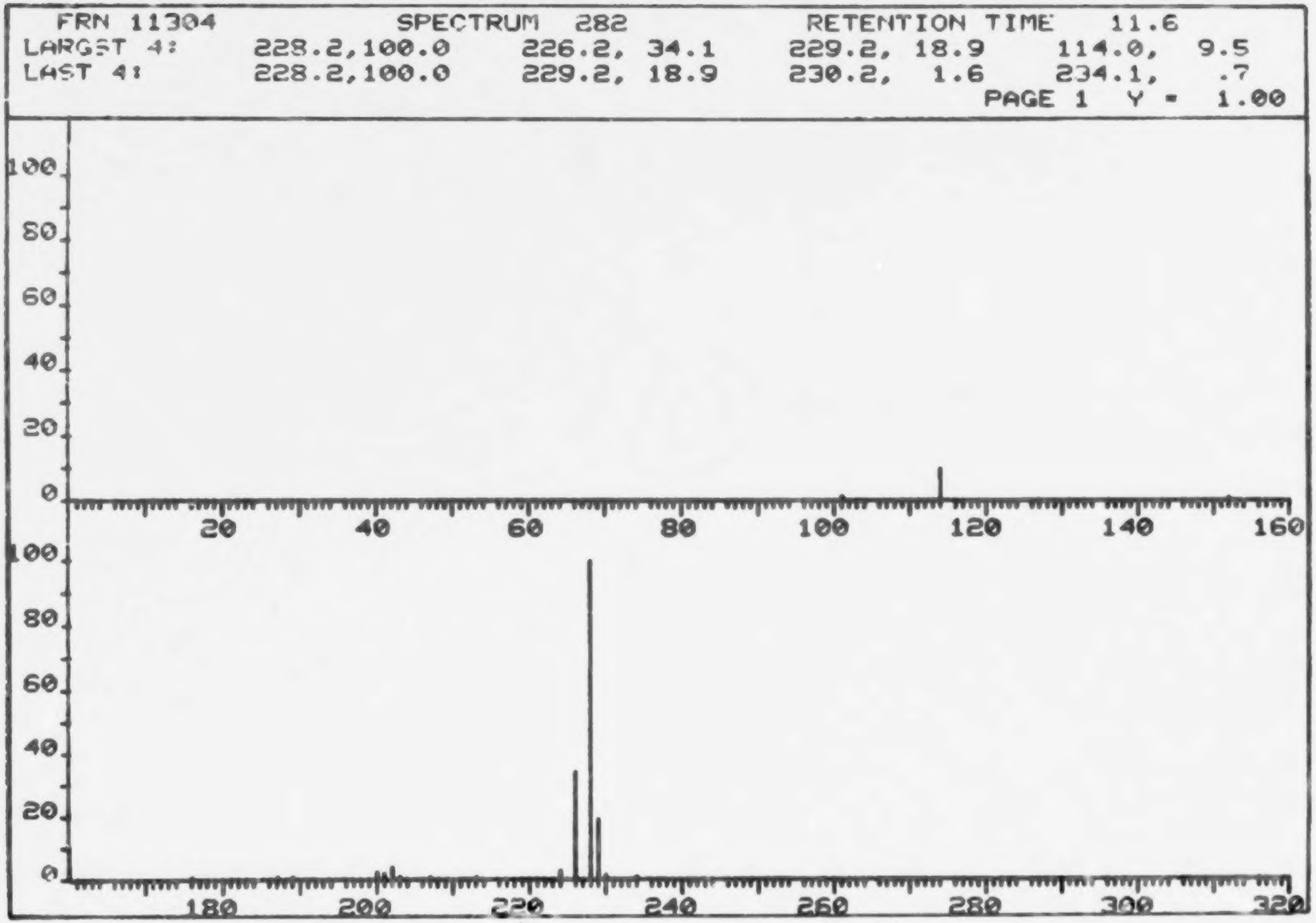
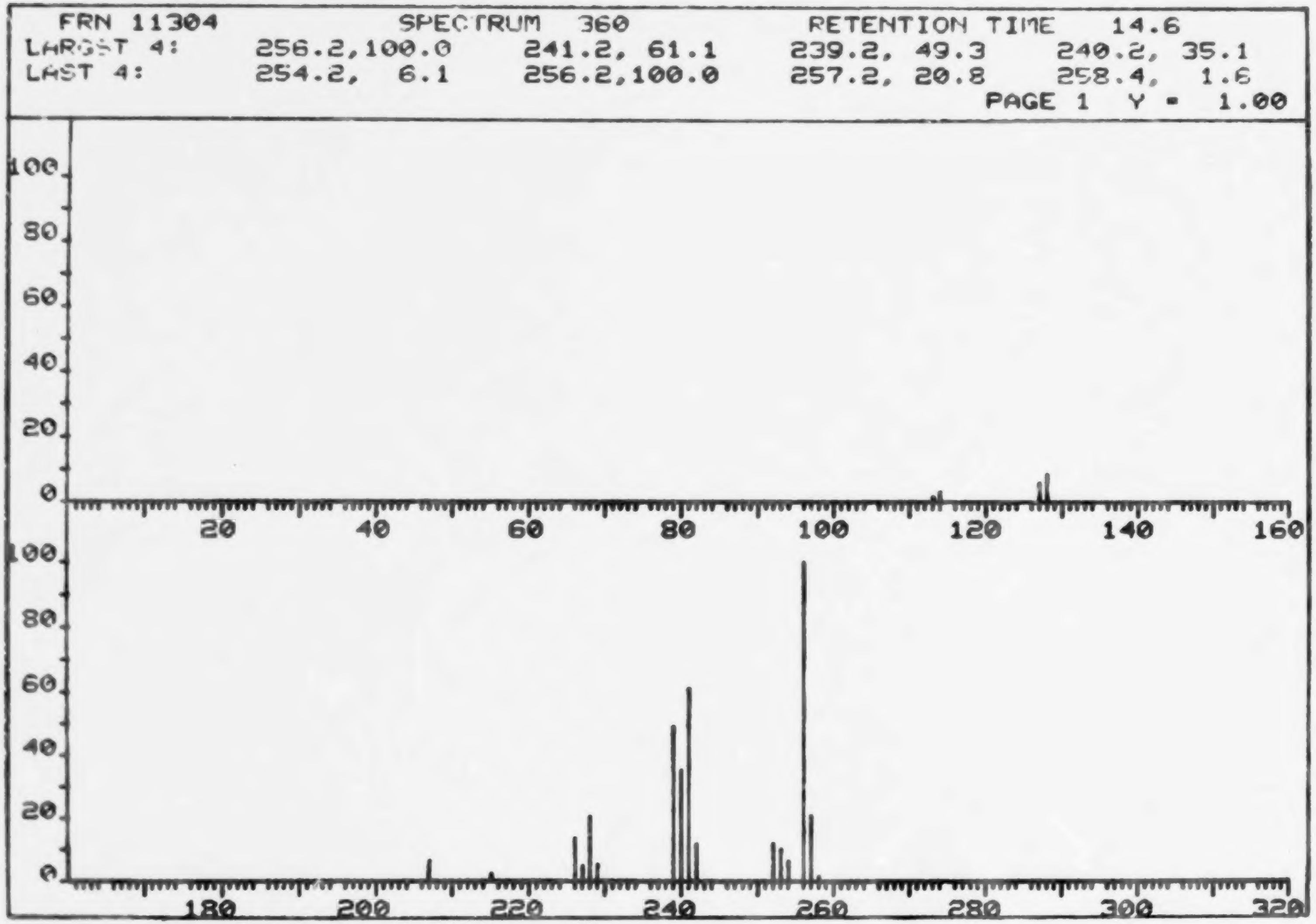
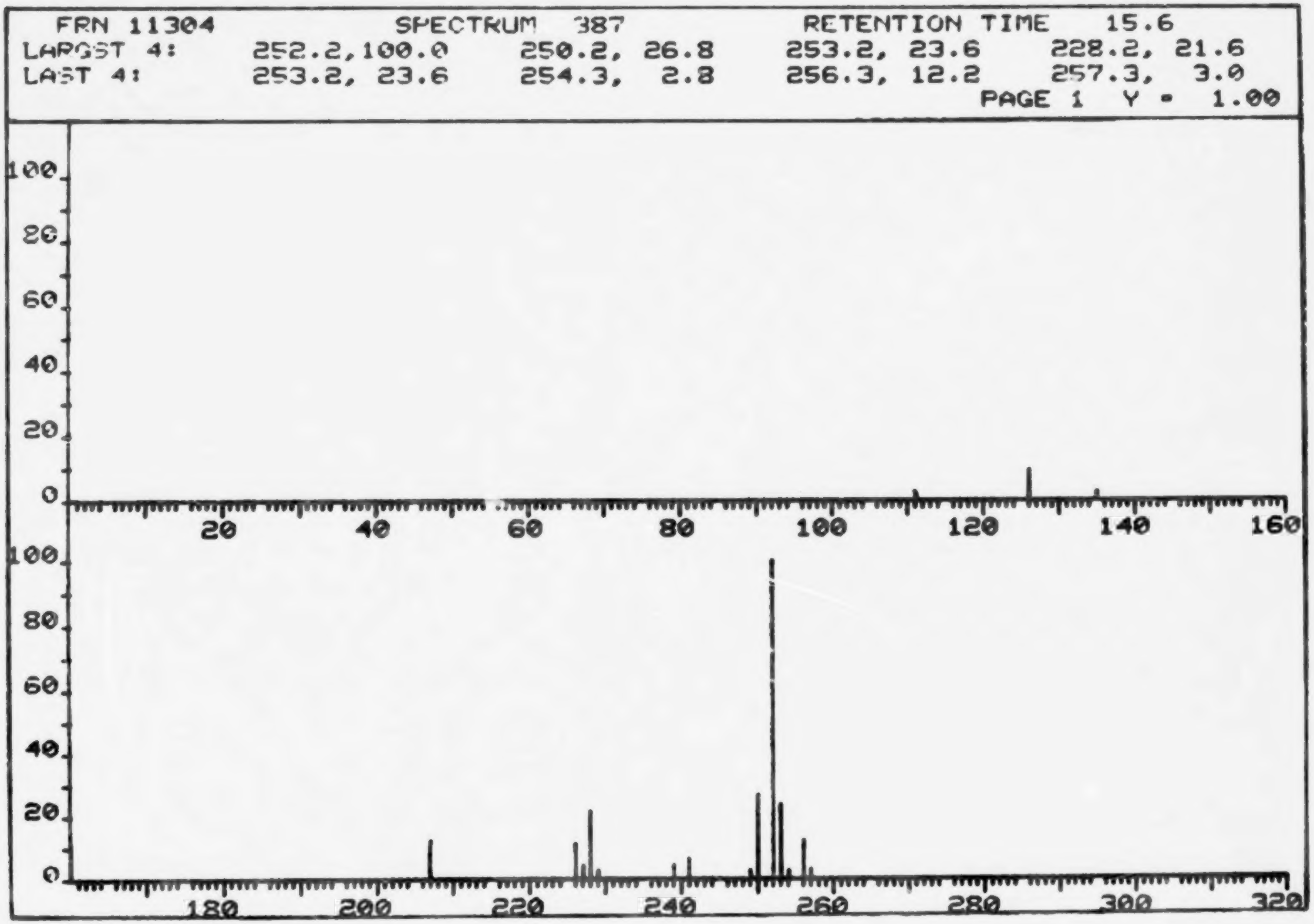


```
 FRN 11304            SPECTRUM  282             RETENTION TIME   11.6
LARGST 4:      228.2,100.0     226.2, 34.1     229.2, 18.9     114.0,  9.5
LAST 4:        228.2,100.0     229.2, 18.9     230.2,  1.6     234.1,   .7
                                                          PAGE 1  Y =  1.00
```



```
 FRN 11304             SPECTRUM  360             RETENTION TIME   14.6
LARGST 4:     256.2,100.0     241.2, 61.1     239.2, 49.3     240.2, 35.1
LAST 4:       254.2,  6.1     256.2,100.0     257.2, 20.8     258.4,  1.6
                                                          PAGE 1  Y =  1.00
```



```
 FRN 11304            SPECTRUM  387            RETENTION TIME   15.6
LARGST 4:     252.2,100.0     250.2, 26.8     253.2, 23.6     228.2, 21.6
LAST 4:       253.2, 23.6     254.3,  2.8     256.3, 12.2     257.3,  3.0
                                                        PAGE 1  Y =  1.00
```

Monsanto

MONSANTO RESEARCH CORPORATION
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Phone (513) 268-3411
TWX 810-459-1681

23 August 1979

Dr. W. F. Gutknecht
Research Triangle Institute
P.O. Box 12194
Research Triangle Park
North Carolina 27709

Dear Dr. Gutknecht:

Enclosed is a summary report of our GC/MS analysis of your sample RTI PAH-I. We are also enclosing for your information the chromatograms/ion traces for the sample and standard runs as well as the mass spectra of the compounds and the area tables.

I would very much appreciate it if you could forward to me as soon as possible the compound identities and concentrations in the audit sample. Besides being of great utility in evaluating our analytical methods, we plan to present a comparison of our results with the RTI values in our forthcoming sampling report on residential wood combustion emissions.

If you have any questions, please call me or Dr. Joseph Brooks, Research Group Leader, GC/MS technology group.

Sincerely,

Daryl DeAngelis

Daryl DeAngelis

DD/tak
Enclosure

cc Dr. Larry Johnson
    EPA-RTP

    Mr. John Milliken
    EPA-RTP MD-63

a subsidiary of Monsanto Company

Preparation of 7,12 Dimethylbenzanthracene Audit Sample for Monsanto Research Corporation

Introduction

In a report dated June 1978 and titled "Source Assessment: Coal-Fired Residential Combustion Equipment Field Tests, June 1977" (EPA-600/2-78-004o), Monsanto Research Corporation reported finding a level of 7,12 dimethylbenzanthracene (7,12 DMBA) which was about ten times as high as any other POM identified. This fact has caused some alarm as 7,12 DMBA is a potent carcinogen. In order to test the accuracy of both the qualitative and quantitative aspects of the analysis, RTI prepared and sent MRC an appropriate audit sample. MRC sent Arthur D. Little, Inc. an aliquot of the original sample upon which the high 7,12 DMBA results were based; ADL was to perform a verification analysis of this sample. Thus RTI sent an aliquot of its audit sample to ADL to be analyzed along with the original sample. The audit samples were sent to MRC and ADL on May 7, 1979.

Sample Design

The value for 7,12 DMBA reported by MRC in the June 1978 document may well be correct. If it is not correct, two sources of error could be 1) inaccurate identification of the compound, i.e., a compound of mass equal to 7,12 DMBA being incorrectly designated 7,12 DMBA, or 2) poor separation of compounds similar to 7,12 DMBA leading to inaccurate quantification. Most other sources of error, such as miscalculation, have been eliminated. To test these two error sources, it was decided to prepare a mixture of POM's similar to and including 7,12 DMBA which would elute from a Dexsil column (the type used by MRC) as a group. The compounds selected were: 1,2 benzanthracene, chrysene, triphenylene, 7,12 DMBA and benz(a)pyrene.

A "realistic" audit sample would have consisted of a deposit of these compounds on an aliquot of XAD-2 resin, the material used to collect the orginal sample. However, this complex sample would have introduced extraction as a possible error source, which would have the potential of complicating an analysis of the audit results. Thus EPA and RTI decided that the audit sample should be simple, and accordingly, the audit sample consisted of the five compounds dissolved in benzene at concentrations suitably high to prevent interpretation problems due to being near detection limits. The possibility of a second audit sample prepared with XAD-2 resin is still being considered.

Sample Preparation and Verification

The compounds were purchased from commercial sources or obtained from other groups in the Research Triangle Park. All were used without further purification. The compounds (all solids) were weighed out in the RTI Toxic Substances Laboratory and dissolved in Burdick and Jackson benzene. The resultant concentrations are shown in the table below. This solution was analyzed by Dr. Santosh Gangwal of RTI using a Varian 3700 GC and a 25 meter, WCOT, capillary column containing OV101. His results, which have an estimated uncertainty of ±30%, are also shown in this table.

	POM Audit Sample, ug/mL in benzene	
Compound	RTI Expected Value*	GC Value
1,2 benzanthracene	205	171
chrysene	159	(194)**
triphenylene	103	
7,12 DMBA	90	80
benz(a)pyrene	49	41

*Based on gravimetric method of preparation

**A value for chrysene plus triphenylene is reported as these substances are not resolved on the GC system used.

Sample Packaging

Aliquots of several mL each were placed in 7.4mL vials which had been cleaned using the Level 1 procedure for cleaning glassware. The caps used on the vials were Teflon-lined. Also, each cap was secured to the vial with a tube of heat-shrink Teflon overlapping both the vial and the cap.

RESEARCH TRIANGLE INSTITUTE
POST OFFICE BOX 12194
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27709

SYSTEMS AND MEASUREMENTS DIVISION

August 29, 1979

Mr. Daryl DeAngelis
Monsanto Research Corporation
Dayton Laboratory
1515 Nicholas Road
Dayton, Ohio 45407

Dear Mr. DeAngelis:

The results of your GC/MS analysis of the RTI audit sample have been received and compared to expected results. These results are as follows:

RTI AUDIT MIXTURE	MRC ANALYSIS RESULT
1,2 benzanthracene, MW 228, 205 μg/mL	benz(a)anthracene/chrysene (or isomer), MW 228, 467 μg/mL
chrysene, MW 228, 159 μg/mL	*
triphenylene, MW 228, 103 μg/mL	*
7,12 DMBA, MW 256, 90 μg/mL	7,12 DMBA (or isomer) MW 256, 121 μg/mL
benz(a)pyrene, MW 252, 49 μg/mL	benz(a)pyrene/perylene, MW 252, 61 μg/mL
----------	naphthobenzothiophene MW 234, 12 μg/mL

From the ion current trace, it appears that the 1,2 benzanthracene, chrysene and triphenylene were not resolved on your column. The total, expected concentration for these three substances, i.e., 467 μg/mL, matches your value for MW 228 exactly. There is good agreement between expected and reported values for 7,12 DMBA and benz(a)pyrene. The naphthobenzothiophene was not purposely included in the audit mixture; it could be there as an impurity though we have no evidence for its presence.

If you should have any questions regarding these values or the preparation of the audit mixture, please do not hesitate to call.

Sincerely,

William Gutknecht

W. F. Gutknecht, Ph.D.

WFG/nzh

cc: Dr. L. D. Johnson (EPA)
Mr. John Milliken (EPA)

GLOSSARY

ash: The incombustible matter remaining after the incinceration of wood.

baffled stove: A stove structured with a piece of horizontal sheet metal above the fire so that the combustion gases must circulate around the sheet before they leave the stove.

creosote: A colorless or yellowish oily liquid containing a mixture of phenolic compounds. Creosote is usually contained in the tar of woods.

criteria pollutants: Those for which air quality standards have been established.

damper: Valve or plate used to regulate the flow of air to a combustion process.

draft: Pressure difference causing flow of a fluid, usually applied to convection flow as in chimneys.

emission rate: As used in this report: grams of pollutant emitted per kilogram of wood burned.

flue: Enclosed passage for conveying combustion gases to the atmosphere.

green wood: Freshly cut wood containing most of its original moisture content.

nonbaffled stove: A stove which lacks a metal divider between the fire and flue resulting in direct exit of combustion gases.

proximate analysis: Fuel analysis on the basis of percent fixed carbon, volatile matter, moisture, and ash.

seasoned wood: Wood which has been cured by drying to ensure a uniform moisture content.

soot: Impure black carbon with oily compounds obtained from the incomplete combustion of resinous materials, oils, wood, or coal.

ultimate analysis: Fuel analysis on the basis of elemental content; namely, carbon, hydrogen, oxygen, nitrogen, sulfur, and ash.

zero clearance fireplace: A fireplace with enough air space around its heated surfaces that allows it to be placed next to a combustible wall.

CONVERSION FACTORS AND METRIC PREFIXES (33)

CONVERSION FACTORS

To convert from	To	Multiply by
Degree Fahrenheit	Degree Celsius (°C)	$t_{°C} = (t_{°F} - 32)/1.8$
Degree Celsius	Kelvin (°K)	$t_{°K} = t_{°C} + 273.15$
Pound-mass	Gram (g)	4.535×10^{2}
Pounds/hour	Gram/second (g/s)	1.260×10^{-1}
British thermal unit (Btu)	Joule (J)	1.055×10^{3}
Pound mass (avoirdupois)	Kilogram (kg)	4.535×10^{-1}
Ton (short, 2,000 lb mass)	Kilogram (kg)	9.074×10^{2}
Pound mass/foot^3	Kilogram/meter^3 (kg/m^3)	1.602×10^{1}
Mile^2	Kilometer^2 (km^2)	2.591
Foot	Meter (m)	3.048×10^{-1}
Inch	Meter (m)	2.540×10^{-2}
Foot^3	Meter^3 (m^3)	2.832×10^{-2}
Pound-mass	Metric ton	4.535×10^{-4}
Pound-force/in^2 (psi)	Pascal (Pa)	6.897×10^{3}

METRIC PREFIXES

Prefix	Symbol	Multiplication factor	Example
Giga	G	10^{9}	1 Gg = 1×10^{9} grams
Mega	M	10^{6}	1 MJ = 1×10^{6} joules
Kilo	k	10^{3}	1 kPa = 1×10^{3} pascals
Milli	m	10^{-3}	1 mg = 1×10^{-3} gram
Micro	µ	10^{-6}	1 µm = 1×10^{-6} meter

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(33) Standard for Metric Practice. ANSI/ASTM Designation E 380-76$^{\varepsilon}$ Std 268-1976, American Society for Testing and Materials, Philadelphia, Pennsylvania, February 1976. 37 pp.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES IERL-RTP project officer is John O. Milliken, Mail Drop 63, 919/541-2745.

16. ABSTRACT The report describes a study to quantify criteria pollutants and characterize other atmospheric emissions from wood-fired residential combustion equipment. Flue gases were sampled from a zero clearance fireplace and from two airtight cast iron stoves (baffled and nonbaffled). Four woods were tested: seasoned and green oak and seasoned and green pine. Samples were analyzed for particulates, condensable organics, NOx, CO, SOx, organic species, and individual elements. Considerable variability was observed in results under different test conditions. Average emission factors compared favorably with other studies on residential wood combustion. In most cases, variations in emission factors could not be correlated with either combustion equipment or wood type, and were ascribed to systematic errors or the effect of such variables as excess air level and wood arrangement. Combustion equipment influenced emissions of CO, NOx, and POMs. Emissions of CO and POMs were greater from wood-burning stoves, while NOx emissions were greater from fireplaces. The only significant effect from wood type was the production of more organic materials during combustion of green pine. Particulate emissions were organic (50% to 80% carbon) and of resinous quality. More condensable organics were emitted than filterable particulate.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Residential Buildings	Pollution Control	13B	11M
Wood		Stationary Sources	11L	
Combustion		Wood Stoves	21B	
Fireplaces			13A	
Stoves				
Chemical Properties			07D	

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